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This report describes research on eleven different projects ranging from fundamental quantum optics to optical systems engineering. Some of the important results include: The demonstration of a prototype all solid state intracavity Raman laser for sodium guide star generation in adaptive optics; the demonstration of a prototype generalized aspheric interferometer; the development of a real-time electronic holographic moire system for measuring stress of mechanical components; the development of enhanced techniques for near-field scanning optical microscopy; the characterization of photoactive yellow protein as a media for optical signal processing; the development of a theoretical basis for nonlinear atom optics leading to the generation of a coherent atomic beam; the demonstration of optical trapping of a single Cs atom far off resonance; the characterization of semiconductor quantum well systems; and the demonstration of prototype circular grating surface emitting distributed Bragg grating lasers. The JSOP program supported over 26 graduate students and resulted in over 71 publications. The Optical Sciences Center hosted a review of the JSOP program for DOD laboratory personnel and hosted workshops on quantum cryptography and on atom optics.

14. SUBJECT TERMS Nonlinear optics, photoactive yellow protein atom optics, semiconductor quantum wells, lasert, optical lattices, guide star laser, optical solitons, holographic moire aspheric interferometer, NSOM

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August 1997

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CONTENTS

EXECUTIVE SUMMARY

This report covers work accomplishted at the University of Arizona, Optical Sciences Center, during the period from December 15, 1993 through May 14, 1997, supported by the Joint Services Optics Program. This final report describes results obtained from eleven research projects, spanning the field of optics from fundamental quantum optics theory to the engineering design of optical siystems. These projects supported more than 20 graduate students and several postdoctoral associates, and the research effort culminated in the publication of five dissertations, the most important aspects of which are listed below. They have been published by University Microfilms, Inc. (UMI), and are readily available from UMI, The University of Arizona Main Library, and the Optical Sciences Center's Fred A. Hopf Reading Room.

Thomas C. Zaugg, "Cavity QED: Adiabatic Atomic Cooling in Cavities, and Evaluation of a Technique for Atomic Homodyning Detection of Cotangent States," University of Arizona (1994). This thesis analyzed how a decaying cavity field can lead to signficant atomic cooling. It also includes an evaluation of a nonlinear atomic homodyne detection scheme for measuring the Wigner characteistic function of a microwave cavity field.

Elena V. Goldstein, "Nonlinear Atom Optics", University of Arizona (1996). The goal of this research was to study selected aspects of nonlinear atom optics. Specifically, the near-resonant dipole-dipole interaction between two atoms in tailored vacua; the study of several aspects of the many-body theory of atomic ultracold systems in situations where

the nonlinearity arises due to the two-body dipole-dipole interaction; and the elementary excitations and the quasi-particle frequency spectrum in a multicomponent Bose condensate.

J. L. Kann, "Numerical Modeling of a Near-Field Optical System", University of Arizona (1995). A hybrid finite-difference-time-domain (FDTD)/angular spectrum code was used to study the electromagnetic and imaging properties of a near-field scanning optical system.

F. F. Froehlich, "Resolution and Contrast of Optical and Shear Force Imagery in Near-Field Scanning Optical Microscopy", University of Arizona (1995). Mechanisms that influence image formation in near-field scanning optical microscopy performed with tapered fiber aperture probes were investigated.

Byron B. Taylor, "Topics in Atom Optics", University of Arizona (1997). Investigations were performed on the effects of light forces on the center-of-mass motion of two-level atoms, Doppler cooling for ry optics, and an atomic Fabry-Pérot for wave optics.

The projects involved contacts and collaborations with several Department of Defense laboratories including:

U.S. ARMY

Natick Resarch, Development and Enginering Center
Materials Command
Harry Diamond Laboratory
Edgewood Research, Development and Engineering Center

U.S. AIR FORCE

Phillips Laboratory
Rome Air Development Center
Brooks Air Force Base
Flight Dynamics Laboratory Wright Patterson Air Force Base
Wright Lab

A complete list of all personnel, publications, and inventions are listed below:

Personnel Supported by the Joint Services Optics Program

Galina Khitrova, Principal Investigator, "Nonlinear Optics in Vapors and Electron Optics"
Tom Nelson, Jr.
David Wick
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Jill Berger
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Hyatt Gibbs/Michael A. Cusanovich, Principal Investigators, "Photoactive Yellow Protein"
Gordon Tollin
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Savitha Devanathan
C.F. Li

Pierre Meystre, Principal Investigator, "Atom Optics"
G. Lenz
T. C. Zaugg
E. V. Goldstein
M.G. Moore
P. Pax
B. B. Taylor

Rudolph H. Binder, Principal Investigator, "Theory of Ultrafast Nonlinear Optical Response of Uniaxially Strained Semiconductor Quantum Wells"
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Richard Powell, Principal Investigator, "Sodium Guide Star Laser"
James Murray

Ewan Wright, Principal Investigator, "Ultra-Short Pulse Propagation and the Quantum Statistics of Optical Solitons"
Augusto Rodrigues
Keith Kusanic
Kirk Cook

Katherine Creath, Principal Investigator, "Real-Time Electronic Holographic Moiré"
Norbert Sigrist
Joanna Schmit
Peter Ettl

John Greivenkamp, Principal Investigator, "Development of a Generalized Aspheric Interferometer"
A. E. Lowman

Tom Milster, Principal Investigator, "Micro-Optics and Near-Field Scanning Optical Microscopy (NSOM)"
J. Kann
F. Froehlich

GALINA KHITROVA'S PUBLICATIONS

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MAHMOUD FALLAHI'S PUBLICATIONS

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POUL JESSEN'S PUBLICATIONS

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RICHARD POWELL'S PUBLICATIONS

None

EWAN WRIGHT'S PUBLICATIONS

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KATHY CREATH'S PUBLICATIONS

None

JOHN GREIVENKAMP'S PUBLICATIONS

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Richard C. Powell, Director
Optical Sciences Center
August 1997

NONLINEAR OPTICS AND ELECTRON OPTICS

Galina Khitrova

Statement of the Problem Studied

The goal was to grow narrow-linewidth quantum wells inside a semiconductor microcavity by MBE and study the linear, nonlinear, and photoluminescence properties of this strongly coupled system of exciton and cavity mode. Cavity QED effects in semiconductor microcavities may someday lead to improved lasers and light-emitting diodes.

Abstract of the Most Important Results

InGaAs/GaAs quantum wells with record narrow linewidths less than 1 meV have been grown inside a semiconductor microcavity consisting of GaAs/AlAs distributed Bragg reflectors and a GaAs spacer. Vacuum Rabi splitting or normal mode coupling results because of the strong coupling between these two oscillators, namely the exciton and the cavity mode. The quantum-well narrow linewidth and the high-finesse cavity result in record values of the splitting to linewidth ratio. This permitted the observation of a new nonlinear effect: with increased excitation the transmission of the coupled system goes to zero with negligible reduction in the splitting. Measuremnts on quantum wells outside the cavity reveal that at densities below the onset of state filling and bandgap renormalization the exciton broadens with little change in oscillator strength. By correlating the nonlinear transmission with the photoluminescence, it was established that the density is too high for excitons to behave as Bosons when the upper polariton

emission increases rapidly compared to the lower. This impressive crossover, called by some Boser action and attributed to condensation into the upper polariton, results from the density dependence of both the emitters and the photon density of states.

Summary of the Principal Findings

Nonlinear Behavior of Vacuum-Field Rabi Splitting in Semiconductor Microcavities

We have grown InGaAs/GaAs quantum wells with very narrow linewidths (1 meV = 0.6 nm). By growing one of these in the center of a one-wavelength GaAs spacer or two in the two central anti-nodes of a 3l/2 microcavity, we have observed record splitting-to-linewidth ratios (>10) of so called vacuum Rabi splitting (VRS) at 4K. This phenomenon is also known as normal mode coupling because it exhibits the characteristic anti-crossing curve of two coupled oscillators (here exciton and cavity) as their relative detuning is scanned through zero. We have increased the splitting, seen in reflectivity or transmission, by placing the microcavity in a magnetic field up to 12T, showing that the splitting depends linearly on the electric dipole moment (published in Physical Review B). We have also seen record depth of modulation vacuum field Rabi oscillations because of the high quality of our samples. We have studied the nonlinear transmission and reflection of our VRS microcavities both by cw pump/probe and by femtosecond reflection and upconversion. Because of our very narrow lines we see a *new nonlinear behavior: the transmission drops to zero with almost no reduction in VRS*; this is explained by nonlinear dispersion theory using the measured exciton absorption with increased carrier density in a transfer matrix formalism. *The basic physics is exciton*

broadening before loss of oscillator strength; as the exciton broadens the absorption increases at the detuned wavelengths of the VRS transmission peaks thus decreasing the Fabry-Perot transmission (a little bit of absorption in a high-finesse cavity destroys its transmission). Since the area under the exciton absorption (proportional to oscillator strength) changes very little as the broadening sets in, there is almost no reduction in splitting while the transmission drops to zero. This curious nonlinear behavior could not be seen by other groups whose VRS samples were so inhomogeneously broadened that exciton broadening had little effect. The cw nonlinear measurements and agreement with a many-body theory (with Stephan Koch & Frank Jahnke, Marburg, Germany) have been published in Physical Review Letters. Next we made extensive measurements on the photoluminescence spectra of VRS samples as a function of excitation density and correlated them with the nonlinear transmission. From such measurements and many-body calculations of the Bosonic commutator, we established that the rapid increase in the upper polariton emission relative to the lower polariton is not a result of condensation or final state stimulation as proposed by others. Instead it is simply the emission of an excitation-dependent distribution of emitters within a microcavity whose photon density of states is also excitation dependent. (Submitted to Phys. Rev. Lett.) The measurements described so far were performed at 4K, but recently we have achieved record room-temperature normal-mode coupling using InGaAs/GaAs quantum wells in a microcavity with aluminum-oxide/GaAs mirrors (published in Appl. Phys. Lett.).

List of all Publications and Technical Reports

Publications in refereed journals:

1. H. M. Gibbs, G. Khitrova, C.W. Lowry, and S. W. Koch, "Acceleration of coherent transfer of energy by stimulated emission and absorption," Opt. and Phot. News 14 (Dec. 1994).

2. R. Jin, G. Khitrova, D. Boggavarapu, H. M. Gibbs, S. W. Koch, M. S. Tobin, and R. P. Leavitt, "Physics of semiconductor vertical-cavity surface-emitting lasers," J. Nonlin. Opt. Phys. and Matls. **4**, 141-161 (1995). Invited paper.

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4. P. G. Baranov, N. G. Romanov, I. V. Mashkov, G. Khitrova, H. M. Gibbs, and O. Lyngnes, "Local diagnostics of GaAs/AlAs superlattices using optically detected magnetic resonance and level anticrossing effect," Solid State Physics **37**, 1648 (1995).

5. T. R. Nelson Jr., E. K. Lindmark, D. V. Wick, K. Tai, G. Khitrova, and H. M. Gibbs "Normal-mode coupling in planar semiconductor microcavities," in J. Rarity and C. Weisbuch, eds., *Quantum Optics in Wavelength Scale Structures* (NATO, 1995).

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9. E. K. Lindmark, T. R. Nelson, Jr., G. Khitrova, H. M. Gibbs, A. V. Kavokin, and M. A. Kaliteevski, "Three coupled oscillators: normal mode coupling in a microcavity with two different quantum wells," Opt. Lett. **21**, 994 (1996).

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11. T. R. Nelson, Jr., J. P. Prineas, G. Khitrova, H. M. Gibbs, J. D. Berger, E. K. Lindmark, J.-H. Shin, H.-E. Shin, and Y.-H. Lee, "Room-temperature normal-mode-coupling in a semiconductor microcavity utilizing native-oxide AlAs/GaAs mirrors," Appl. Phys. Lett. **69**, 3031 (1996).

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1. G. Khitrova, "Coherent energy transfer in microcavity lasers," MF2, 1994 Conference on Interdisciplinary Laser Science.
2. G. Khitrova, "Acceleration of coherent transfer of energy by stimulated emission and absorption," 1994 Annual Meeting of the IEEE Lasers and Electro-Optics Society.
3. G. Khitrova, "Cavity quantum electrodynamics," Nonlinear Optical Materials and Applications '95, Cetraro, Italy, June 2, 1995.
4. G. Khitrova, "Vortices and transverse mode control in vertical-cavity surface-emitting lasers," Laser Optics '95, St. Petersburg, Russia, June 30, 1995.
5. G. Khitrova, "Semiconductor microcavity phenomena," International Conference on Nonlinear Optics, Physics and Applications, Harbin, China, July 18-24, 1995.

6. G. Khitrova, "Vacuum Rabi splitting in a semiconductor microcavity," Korea Advanced Institute for Science and Technology, Taejon, Korea, July 28, 1995.
7. G. Khitrova, "Physics of semiconductor light sources," ARPA Optics Review, Big Sky, Montana, August 3, 1995.
8. G. Khitrova, "Vacuum Rabi splitting," NATO Workshop on Quantum Optics in Wavelength Scale Structures, Cargese, Corsica, France, Aug. 29, 1995.
9. G. Khitrova, "Cavity quantum electrodynamics," Philipps University, Marburg, Germany, December 14, 1995.
10. G. Khitrova, "Normal mode coupling, three lectures, April 10-12, 1996, Philipps University, Marburg, Germany.
11. G. Khitrova, "Nonlinear cw pump-probe and femtosecond reflectivity measurements of semiconductor microcavities exhibiting normal-mode coupling," Optical Properties of Mesoscopic Semiconductor Structures, Snowbird, May 7-10, 1996.
12. G. Khitrova, "Semiconductor microcavity QED," Physics Department, University of Oregon, Eugene, November 15, 1996.
13. G. Khitrova, "Photoluminescence and transmission of vacuum Rabi splitting semiconductor microcavities as a function of excitation," 26th Winter Colloquium on the Physics of Quantum Electronics, Snowbird, Utah, January 12-15, 1997.
14. G. Khitrova, "Excitonic nonlinearities and photoluminescence of semiconductor microcavities in the nonperturbative regime," International Winter School on the Physics of Semiconductors, 1-5 March, 1997, St. Petersburg, Russia.

15. G. Khitrova, "Nonlinear vacuum Rabi splitting in semiconductor microcavities," 3rd Mediterranean Workshop and Topical Meeting on Novel Optical Materials and Applications, Cetraro, Italy, June 8-13, 1997.

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   Room-Temperature Semiconductor Microlaser," QThI4, 1995 Conference on Quantum Electronics and Laser Science.
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Type-II GaAs/AlAs Superlattices," International Symposium on Compound Semiconductors, St. Petersburg, Russia, September 23-27, 1996.

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16. J. D. Berger, S. Hallstein, W. W. Ruhle, O. Lyngnes, G. Khitrova, H. M. Gibbs, M. Kira, F. Jahnke, and S. W. Koch, "Cavity-Polariton Formation and Relaxation Dynamics in Semiconductor Microcavities," OSA Topical Meeting on Quantum Optoelectronics, March 19-21, 1997, Incline Village, Nevada.
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Inventions

None

NONLINEAR OPTICAL PROPERTIES OF PHOTOACTIVE YELLOW PROTEIN

Hyatt M. Gibbs and Michael A. Cusaonovich

Statement of the Problem Studied

Bacteriorhodopsin (BR) has been studied and promoted as a medium for optical signal processing. Photoactive yellow protein (PYP), first isolated at the University of Arizona, is a smaller and better characterized molecule with linear optical properties similar to BR. The goal of this research project was to measure the nonlinear optical properties of PYP and to evaluate its potential for optical signal processing and storage relative to PYP.

Abstract of The Most Important Results

The one-photon nonlinear absorption of PYP was measured by pump/probe spectroscopy. Kramers-Kronig transformations on those data yielded the corresponding nonlinear refractive index as a function of wavelength. The peak-wavelength change in index per excited molecule for PYP is almost the same as that of PYP, suggesting that they have similar one-photon responses.

An extended effort was made to measure the two-photon absorption cross section of PYP without success. An upper limit of 3.5 X 10^{-52} cm^4 s $molecule^{-1}$ $photon^{-1}$ was determined, 10,000 times smaller than that reported for BR. Consequently, PYP is no competitor with BR as a 3D optical data storage medium, if the reported BR cross section is correct. Efforts to reproduce the BR results on available samples were unsuccessful; others have also failed to reproduce the BR results.

During the course of this project substantial progress was made in the methods of growing and purifying PYP and forming new forms of PYP by mutagenesis.

The details of this entire research effort are contained in an article to be published in the Journal of Nonlinear Optical Physics and Materials.

List of All Publications and Technical Reports

1. Lyngnes, E. K. Lindmark, M. Switala, H. M. Gibbs, T. E. Meyer, G. Tollin, and M. A. Cusanovich, "Nonlinear Optical Properties of Photoactive Yellow Protein," CLEO '94.
2. Lyngnes, H. M. Gibbs, C. F. Li, S. B. Devanathan, T. E. Meyer, G. Tollin, and M. A Cusanovich, "One-Photon and Two-Photon Pump-Probe Spectroscopy of Photoactive Yellow Protein," J. Nonlinear Optical Physics and Materials, to be published.
3. Lyngnes, H. M. Gibbs, C. F. Li, S. B. Devanathan, T. E. Meyer, G. Tollin, and M. A Cusanovich, "One-Photon and Two-Photon Pump-Probe Spectroscopy of Photoactive Yellow Protein," Final Report on Rome Laboratories F3060295C0100, May 1996.

Scientific Personnel

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Inventions None

ATOM OPTICS

P. Meystre

Research Findings

The last few years have been very exciting ones indeed in the fields of Quantum Optics and Atomic Physics. Many exciting new developments have taken place, ranging from quantum state preparation and control, with potential applications in quantum computing, to atom optics, atomic cooling and the recent realization of Bose condensation in alkali vapors and the first demonstration of a primitive atom laser.

Our earlier research and research plans found us well positioned to take advantage of, and contribute to, these latter developments. In particular, our work on *nonlinear atom optics* gained considerably in relevance in view of the fact that low density, even multicomponent quantum degenerate atomic vapors are now available.

It is interesting to recall that in our 1994 JSOP annual report, we stated: "...One major goal for the next years is to fully assess the potentiality of nonlinear atom optics, in particular in the realization of "coherent atomic beam generators", sometimes called "lasers for atoms." [...] This is a high-risk field of investigations, but with considerable potential pay-off. We feel that the realization of coherent atomic beam generators, while still a long-term goal, should be of considerable interest both for the DoD and for industry. More generally, the laser manipulation of atomic trajectories appears to rapidly reach the level of sophistication that will lead to emerging new technologies such as atomic lithography, etc... ."

At that time, Bose-Einstein condensation of low density atomic vapors was still only a hope, and "atom lasers" sounded almost like science fiction. In retrospect, the progress achieved since then has been nothing short of amazing, and the picture of an experimentally realized "atom laser" beam even made the cover of Physics Today.

Viewed in this larger context, our own progress has been rather modest, but still, we have made what we believe to be a series of useful, and sometimes trailblazing contributions to that field. A brief summary of highlights includes:

Atom Lasers: Early on, we have proposed an atom laser scheme using the combined effects of dipole-dipole interactions and Bose enhancement in a quasi-one-dimensional cavity to achieve a coherent atomic state in one of the resonator modes. We have carried out a detailed evaluation of the dipole-dipole selection rules between center-of-mass modes of the atoms in the matter-waves cavity, and studied the role of dimensionality on these cross-sections, confirming that a quasi one-dimensional cavity appears to be the geometry of choice.

A major breakthrough occurred when we discovered an elegant and simple way to circumvent the effects of energy-momentum mismatch characteristic of most light-matter wave interactions: While the dipole-dipole matrix elements provide rather strict center-of-mass momentum selection rules, these are largely eliminated by the energy mismatch resulting from the quadratic dispersion relation of matter waves. We found that this problem can be completely eliminated by modulating the light fields that form the matter-waves resonator at the frequency corresponding to this energy defect.

Following this work, we have developed a master equation describing the dynamics of the atom laser, so as to gain an understanding of the dynamics of statistical properties of the system, its linewidth, etc. We have determined the below- and above threshold behaviors and identified the role of collisions in achieving "laser action."

Future work will involve the study of higher-order correlation functions of the matter field, the linewidth of the atom laser, etc.

Quantum Transport on Optical Lattices: Another aspect of nonlinear atom optics that we have began to investigate is the study of quantum transport in optical lattices: The cooling and trapping of atoms in one-, two-, and three-dimensional optical lattices opens up the way to a number of fascinating investigations. In particular, the availability of such systems provides a unique probe of quantum transport, covering situations from the extreme case where deep lattice wells tend to pin the atoms to sites, so that their dynamics becomes analogous to that of a spin lattice, to the full-fledged quantum transport of atoms between wells. Our research has progressed in two main directions:

First, we have been able to give a complete static description of the near-resonant dipole-dipole potential in 3-dimensional optical lattices. We have also studied this interaction using a second-quantized formalism and a Wannier functions basis to evaluate the effects of bound-bound, bound-free and free-free transitions on lattices. This work will be useful in the future in developing a full manybody theory of transport on lattices.

Second, we have carried out a detailed numerical analysis of atomic transport in one-dimensional lattices, both semiclassically and quantum mechanically, but neglecting

so far the effects of atom-atom interactions. Several regimes of transport have been identified, including anomalous diffusion and Levy flights for intermediate lattice depths. While there are quantitative differences between the quantum-mechanical and semiclassical predictions, the qualitative results of these two approaches are rather similar. This is an encouraging result in view of our goal to study transport in higher-dimensional lattices, where full quantum calculations are beyond the capabilities of present-day computers.

Nonlinear Atom Optics and Bose Condensation: In addition to this work, we have carried out research more directly related to Bose condensation per say. For example, we have studied the possibility of phase-conjugating de Broglie waves at a Bose condensate. Both our theory of nonlinear atom optics, as well as the Gross-Pitaevskii description of Bose condensates in terms of a nonlinear Schrödinger equation, suggest that this should be the case. Phase conjugation, or time reversal, of matter waves would be of considerable interest both in the context of fundamental studies of irreversibility, and also as possible diagnostic tools for Bose condensates.

In addition, we have begun to extend the Hartree-Fock approach to nonlinear atom optics into a full Hartree-Fock-Bogoliubov theory. In contrast to the case of "traditional" Bose condensation, which involves scalar Schrödinger fields only, general nonlinear atom optics involves vector (multicomponent) fields, and hence leads to a much richer family of quasi-particle excitations. We have studied the dispersion relations of these quasiparticles in some simple cases, and find regimes of instability where the

condensate solution is expected to be subjected to modulational instabilities. Shortly after our first results were sent for publication, the JILA group announced the experimental realization of a two-component condensate, to which our model can readily be applied. With this experimental breakthrough, the study of multicomponent matter wave fields has become reality and promises to become very important in the near future.

Army Contacts

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Publications

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1. T. Zaugg, P. Meystre, G. Lenz and M. Wilkens, "Theory of Adiabatic Cooling in Cavities," Phys. Rev. A **49**, 3011 (1994) .
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Invited Presentations

1. P. Meystre, *Nonlinear Atom Optics*, Sixth International Symposium on Quantum Optics, Rotorua, New Zealand (1994).

2. P. Meystre, Codirector, NSF Workshop on the *Quantum Field Theory of Cold Atoms*, Boulder, Colorado 1994.

3. G. Lenz, P. Meystre and K. Schernthanner, *Nonlinear Atom Optics*, NSF Workshop on *the Quantum Field Theory of Cold Atoms*, Boulder, Colorado 1994.

4. P. Meystre, *Nonlinear Atom Optics*, European Quantum Electronics Conference, Amsterdam (1994).

5. P. Meystre, *Phase Conjugation of Matter Waves*, International EEC Workshop on Nonclassical Light, Corvara, Italy (1995).

6. P. Meystre, *Manybody Effects in Atom Optics*, Conference on Quantum Optics in Fundamental and Applied Physics, Grand Targhee, Wyoming (1995).

7. P. Meystre, *Manybody Effects in Atom Optics*, European Research Conference on Quantum Optics, Davos, Switzerland (1995).

8. P. Meystre, *Nonlinear Atom Optics: Review and Recent Progress*, Workshop on Collective Effects in Ultracold Atoms, Les Houches, France, (1996).

9. P. Meystre, *When Atoms Become Waves --- Optics of Ultracold Atoms*, Keynote Lecture, Carl von Siemens Foundation, Munich, Germany (1996).

10. P. Meystre, *Manybody Effects in Atom Optics*, Max-Planck Institute for Quantum Optics Annual Meeting, Schloss Ringberg, Germany (1996).

11. P. Meystre, *An Atom Laser with Modulated Cavity*, VIth International Seminar on Fundamentals of Quantum Optics, Kühtai, Austria (1997).

12. P. Meystre, *When Atoms Become Waves*, Keynote Lecture, XXV Symposium for Humboldt Awardees, Alexander von Humboldt Foundation, Bamberg, Germany (1997).

Scientific Personnel Partially Supported by JSOP

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PhD Degrees

Thomas C. Zaugg, "Cavity QED: Adiabatic Atomic Cooling in Cavities, and Evaluation of a Technique for Atomic Homodyning Detection of Cotangent States," University of Arizona (1994).

Elena V. Goldstein, "Nonlinear Atom Optics," University of Arizona (1996).

Byron B. Taylor, "Topics in Atom Optics", University of Arizona (1997).

Awards and Honors

Humboldt Research Prize for Senior US Scientists

Fellow, American Physical Society

THEORY OF ULTRAFAST NONLINEAR OPTICAL RESPONSE OF UNIAXIALLY STRAINED SEMICONDUCTOR QUANTUM WELLS

Rudolf H. Binder

Abstract

The focus of this project was twofold: first, linear and nonlinear optical properties of uniaxially strained semiconductor quantum wells have been investigated theoretically and, secondly, a theoretical approach to the vectorial mode structure of vertical-cavity surface-emitting lasers (VCSELs) has been developed. As for the first project, a theoretical description for the ultrafast (i.e., femtosecond to picosecond) optical response of uniaxially strained GaAs quantum wells has been developed. This theory takes into account linear and coherent nonlinear exciton effects on a parameter-free microscopic level. Incoherent effects such as charge-carrier scattering were considered only in a preliminary fashion for the anisotropic aspects of bulk GaAs. The theoretical results revealed interesting nonlinear dynamics of the interaction-induced modification of polarization ellipticity in strained quantum wells. As for the vectorial mode structure of VCSELs, a generalized transfer matrix method has been developed, which allows for a three-dimensional vectorial solution of Maxwell's equations for micro-cavity lasers with cylindrical symmetry.

Final Report

In this project, we have investigated theoretically two issues from the general area of optical communication systems: (i) the ultrafast nonlinear optical response of uniaxially strained semiconductor quantum wells and (ii) the vectorial mode structure of vertical-cavity surface-emitting lasers (VCSELs). The relation between these two issues lies in the fact that VCSELs do not necessarily contain perfect cubic quantum wells as active material. There is evidence that in reality these quantum wells are slightly strained, a generally small effect which can have a large effect on the polarization properties of the output light field of VCSELs. A solid theoretical foundation was laid for both issues during this project, and we anticipate that future projects will allow us to combine both theories and eventually arrive at a comprehensive theoretical model of the polarization characteristics of micro-cavity lasers and LEDs. In addition to these long-term goals, the investigation of the nonlinear optical response of uniaxially strained quantum wells complement the experimental development of high-contrast light modulators at the Army Research Laboratory (formerly at Fort Monmouth). Also in the context of microscopic processes in anisotropic structures (ii), we have investigated charge-carrier scattering and quasi-thermalization in bulk GaAs.

All of these subprojects have been supported through the JSOP grant as well as other sources. For the project on strained quantum wells, JSOP was the dominant source of funding.

The first issue (i) consists of several subtopics, out of which the coherent femtosecond nonlinear response was the main focus of this project and required the largest amount of software development.

It is based on the derivation and numerical investigation of the extended semiconductor Bloch equations including the Luttinger hamiltonian to account for strain effects and the Coulomb potential to account for linear and nonlinear excitonic effects. The second sub-topic investigated within this project was the momentum-orientation relaxation of photo-excited charge carriers by means of carrier-carrier scattering in conventional cubic semiconductors, such as ideal bulk GaAs. This laid the foundation for future investigations of carrier-carrier-scattering-induced relaxation and quasi-thermalization processes in anisotropically strained quantum wells, which may be combined in a future research project with the above-mentioned theory of coherent nonlinear optical response of these structures.

All of the above listed subprojects have lead to publications in peer-reviewed journals [J1-J5] and were presented at international conferences [C1-C8]. Ref. [C1] was almost finished when this project started. It is a comprehensive review article on the general theory of the semiconductor Bloch equations. Ref. [J2] may be regarded as an additional publication in the field of femtosecond optical nonlinearities. The specific publication regarding the semiconductor Bloch equations for anisotropic systems is [J5] and the related incoherent scattering theory in anisotropic systems is [J3]. The theory of vectorial electromagnetic modes of VCSELs is presented in [J4].

We begin with the description of the theory of coherent nonlinear optical response of uniaxially strained GaAs quantum wells [1, 2, 3].

The theoretical basis is the Hartree-Fock theory of optically excited thin uniaxially strained semiconductor quantum wells which involves the following equations-of-motion for the time-dependent optical polarization functions $P_{sj}(\vec{k})$, as well as the electron and hole distribution/coherence functions $f_{ss'}(\vec{k})$ and $f_{jj'}(\vec{k})$, respectively. The vector $\vec{k}$ is the two-dimensional in-plane wave vector, the electron quantum numbers s, s' denote the spin-degenerate conduction bands with $s = \pm 1/2$, and the hole quantum numbers j, j' denote the two degenerate heavy-hole ($j = \pm 3/2$) and light-hole ($j = \pm 1/2$) bands. The equations-of-motion (generalized multiband semiconductor Bloch equations [4] are ($\hbar = 1$):

$$
\begin{aligned}
i\frac{d}{dt}P_{sj}(\vec{k}) = \sum_{s'j'} \{ [\delta_{ss'}\delta_{jj'}\varepsilon_k^s + \delta_{ss'}H_{jj'}(-\vec{k}) P_{s'j'}(\vec{k}) \\
- \Omega_{s'j'}(\vec{k}) \left[\delta_{ss'}\delta_{jj'} - \delta_{jj'} f_{ss'}(\vec{k}) - \delta_{ss'} f_{jj'}(\vec{k}) \right] \\
+ \left[\delta_{jj'} \Sigma_{ss'}(\vec{k}) + \delta_{ss'} \Sigma_{jj'}(-\vec{k}) \right] P_{s'j'}(\vec{k}) \} \\
- i(1/T_2) P_{sj}(\vec{k}),
\end{aligned}
\tag{1}
$$

$$
i\frac{d}{dt} f_{ss'}(\vec{k}) = \sum_{j} \{ \Omega^{*}_{s'j}(\vec{k}) P_{sj}(\vec{k}) - \Omega_{sj}(\vec{k}) P^{*}_{s'j}(\vec{k}) \}
$$

$$+\sum_{s''}\{\Sigma_{ss''}(\vec{k})f_{s''s}(\vec{k})-f_{ss''}(\vec{k})\Sigma_{s''s'}(\vec{k})\}, \tag{2}$$

and

$$i\frac{d}{dt}f_{jj'}(\vec{k})=\sum_{j''}\{H_{jj''}(\vec{k})f_{jj''j'}(\vec{k})-f_{jj''}(\vec{k})H_{j''j'}(\vec{k})$$

$$+\sum_{s}\{\Omega^{*}_{sj'}(-\vec{k})P_{sj}(-\vec{k})-\Omega_{sj}(-\vec{k})P^{*}_{sj'}(-\vec{k})\}$$

$$+\sum_{j''}\{\Sigma_{jj''}(\vec{k})f_{j''j'}(\vec{k})-f_{jj''}(\vec{k})\Sigma_{j''j'}(\vec{k})\}. \tag{3}$$

Here, the electron energies are parabolic, $\varepsilon_k^s = \hbar^2k^2/2m_e + E_g'$, where E_g' is the effective band-gap. The Luttinger hamiltonian for the valence bands in the basis $\{j\}$ = (3/2, -1/2, 1/2, -3/2) with basis functions defined in Ref. [5] reads (see also [1])

$$H=\begin{pmatrix} H_{hh} & c^{*} & 0 & 0 \\ c & H_{lh} & 0 & 0 \\ 0 & 0 & H_{lh} & c^{*} \\ 0 & 0 & c & H_{hh} \end{pmatrix} \tag{4}$$

where the hh-hamiltonian is given by $H_{hh} = (\hbar^2/2m_0)(\gamma_1+\gamma_2)(k_x^2+k_y^2)-(1/2)\Delta E_s'(1-2\gamma_s)$, the light-hole (lh) hamiltonian is $H_{lh} = (\hbar^2/2m_0)(\gamma_1-\gamma_2)(k_x^2+k_y^2)+\Delta_{hh-lh}+(1/2)\Delta E_s'(1-2\gamma_s)$ and the

hh-lh coupling is $c = -\left(\hbar_2 / 2m_0\right)\sqrt{3}\left(\gamma_2\left(k_x^2 - k_y^2\right) - 2i\gamma_3 k_x k_y\right) + \left(\sqrt{3}/2\right)\Delta E_s$. The Luttinger parameters are, γ_1, γ_2, γ_2, and the strain contributions $\Delta E_s' = b_s\left(e_{xx} + e_{yy}\right), \Delta E_s = b_s\left(e_{xx} - e_{yy}\right)$, with $\gamma_s = S_{12} / \left(S_{11} + S_{12}\right)$, contain the elastic compliances $S_{11} + S_{12}$, the shear deformation potential b_s, and the strain tensor elements e_{xx} and e_{yy}. The hydrostatic stress component, which merely renormalizes the bandgap energy, as well as the quantum confinement energy, has been put into the definition of E_g' and, therefore, does not occur explicitly. The hh-lh splitting is denoted by Δ_{hh-lh}. The energy renormalizations are given by (with $a = s$ or j)

$$\Sigma_{aa'}(k) = -\sum_{\vec{q}} V(\vec{q}) f_{aa'}\left(\vec{k} + \vec{q}\right) \tag{5}$$

and the renormalized dipole energy is

$$\Omega_{sj}(k) = \vec{\mu}_{sj} \cdot \vec{E} + \sum_{\vec{q}} V(\vec{q}) P_{sj}\left(\vec{k} + \vec{q}\right). \tag{6}$$

The interaction potential $V(q)$ is taken to be the unscreened Coulomb potential in two dimensions. The Jones vector of the negative-frequency contribution of light field, $\vec{E} = \left(\varepsilon_x, \varepsilon_y\right)$, can be written as [6]

$$\vec{E} = \left(\varepsilon_x^0 / 2\right)\vec{e}_x + \left(\varepsilon_y^0 / 2\right)\exp\,(-i\varnothing)\vec{e}_y \tag{7}$$

$$= \left[(\varepsilon_0 / 2)(\cos\theta\cos\varepsilon + i\sin\theta\sin\varepsilon)\right]\vec{e}_x$$

$$+\left[(\varepsilon_0 / 2)(\sin\theta\cos\varepsilon - i\cos\theta\sin\varepsilon)\right]\vec{e}_y\,, \tag{8}$$

where $\vec{e}_x$ and $\vec{e}_y$ are the cartesian unit vectors, ε is the ellipticity angle and θ the azimuth. Right-handed circularly polarized light is defined by $\varepsilon_x = \varepsilon_y$ and $\varnothing = \pi / 2$ and linearly polarized light by $\varnothing = 0$. The dipole matrix elements $\vec{\mu}_{sj}$ contain the information of optical selection rules. Using circular unit vectors $\vec{e}_\pm = \mp\left(\vec{e}_x \pm i\vec{e}_y\right) / \sqrt{2}$, one can write the dipole matrix elements [7] as $\vec{\mu}_{1/2,3/2} = \sqrt{3}\vec{\mu}_{-1/2,1/2} = -\mu\vec{e}_+$ and $\vec{\mu}_{-1/2,-3/2} = \sqrt{3}\vec{\mu}_{1/2,-1/2} = -\mu\vec{e}_-$ where μ is the magnitude of the microscopic cartesian dipole element. Finally, a phenomenological dephasing contribution with dephasing time T_2 has been added to Eq. 1.

From a numerical point of view, the key challenge in the solution of the above equations was the evaluation of the Coulomb integrals, which are of the form of convolutions of the Coulomb potential and material functions such as the polarization and distribution functions. Since $\vec{k}$ is a two-dimensional vector, the integrals are two-dimensional integrals which depend on the two-dimensional vector $\vec{k}$. The resulting numerical complexity had been the reason that all conventional solutions of the semiconductor Bloch equations had been restricted to isotropic systems, in which the

convolution integrals are essentially one-dimensional and depend only on $|\vec{k}|$. The successful completion of this project was, therefore, depending on the question whether optimized algorithms could be found to solve the anisotropic semiconductor Bloch equations. It turned out that the community of nuclear physicists had successfully dealt with mathematically similar problems by means of Fast-Fourier-Transform (FFT) algorithms. The basic idea is to use FFT to transform the functions to be convoluted from momentum into real space, perform the product, and transform the product back via FFT to momentum space. This yields the desired convolution integral. The application of this general idea to the specific problem of the multiband semiconductor Bloch equations resulted in a large numerical code which ran on Convex as well as Cray C-90 computers. The time-integration is performed via a standard 4th order Runge-Kutta method and, for the calculation of optical spectra, the subsequent Fourier transform from time to frequency space is performed via standard integration routines (i.e., not necessarily FFTs). A typical time-integration over several picoseconds required on the order of 10 minutes to 1 hour Cray CPU time.

The numerical results were tested thoroughly to yield the correct behavior for the excitonic dichroism in the linear optical regime. In addition to comparisons with analytically known limiting cases (i.e., linear regime without Coulomb interaction), the comparison with experimental results obtained at ARL confirmed the correct use of the Luttinger hamiltonian and the exciton contributions to the equations-of-motion.

As described in detail in Ref. [J5], very interesting results can be obtained in the single-pulse configuration for the interaction-induced polarization rotation. Here, the repulsive interaction between excitons is the main cause of the nonlinear response. Pauli-blocking and saturation effects have been found to be less dramatic.

As for the issue of incoherent scattering processes, the corresponding subproject was integrated into a collaboration with a group of nuclear physicists. The results on momentum-orientation relaxation via electron-electron scattering in cubic bulk GaAs crystals was published in Ref. [J3]. The theoretical basis is the incoherent part of the generalized semiconductor Bloch equations. This part is best known as generalized quantum Boltzmann equations or Kadanoff-Baym equations. For a one-component electron plasma, these equations describe the time-evolution of the two-time one-particle Green's functions $g^{\gtrless}(\vec{k},t,t')$:

$$\left(i\hbar\frac{\partial}{\partial t}-\varepsilon_{\vec{k}}^{e}\right)g^{\gtrless}(\vec{k},t,t')=$$

$$\int_{t_0}^{t}d\bar{t}\left\{\Sigma^{>}(\vec{k},t,\bar{t})-\Sigma^{<}(\vec{k},t,\bar{t})\right\}g^{\gtrless}(\vec{k},\bar{t},t')-$$

$$\int_{t_0}^{t'}d\bar{t}\,\Sigma^{\gtrless}(\vec{k},t,\bar{t})\left\{g^{>}(\vec{k},\bar{t},t')-g^{<}(\vec{k},\bar{t},t')\right\}. \tag{9}$$

Within the screened-Hartree Fock approximation and the additional approximation of quasi-static screening, the self energy $\Sigma^{\gtrless}\left(\vec{k},t,t'\right)$ is given by

$$\Sigma^{\gtrless}\left(\vec{k},t,t'\right)=\sum_{\vec{k}',\vec{q}}2W(q,t)W(q,t')g^{\gtrless}\left(\vec{k}+\vec{q},t,t'\right)g^{\gtrless}\left(\vec{k}'-\vec{q},t,t'\right)g^{\lessgtr}\left(\vec{k}',t',t\right), \qquad (10)$$

where $W(q,t)=4\pi e^2/\left(q^2+k^2(t)\right)$ is the quasi-statically screened Coulomb potential in Gauss units. Here, $e^2=e_0^2/\varepsilon_b$ is the effective charge squared (e_0 is the electron charge in vacuum and ε_b is the background dielectric constant of the semiconductor) and κ is the screening wavenumber. As for the initial condition, we assume that at the initial time t_0 all correlations vanish and that the equal-time Green's function $-i\hbar g^{<}\left(\vec{k},t_{0,}t_0\right)$ is the initial distribution discussed above. Due to the specific retardation described by Eqs. 9 and 10, the initial condition at a single point in the $t-t'$ plane is sufficient to obtain the solution for all $t,t'>t_0$. The carrier distribution function is finally obtained from $f\left(\vec{k},t\right)=-i\hbar g^{<}\left(\vec{k},t,t\right)$.

The basic development of numerical algorithms of the anisotropic version of the Kadanoff-Baym equations was not part of this project, for they had been developed by the nuclear physicist taking part in this collaboration. The main goal of this project was the application of the Kadanoff-Baym equations to the case of a photo-excited electron plasma in a semiconductor. The hole plasma has been neglected to simplify the problem.

To include the effects based on the Luttinger hamiltonian into the analysis, the initial condition of the time integration of the Kadanoff-Baym equations were chosen in the following way. We followed Zakharchenya *et al.* [8] and used an angle dependence of the two electron components (one due to hh-c excitation and the other due to lh-c excitation) that results form perturbation theory of the optical excitation process with linearly polarized light. We denote the angle between a given momentum state $\vec{k}$ and the polarization vector of the light as θ. As shown in [8] the momentum dependent squared dipole matrix elements $|< c,\vec{k}|\vec{r}\cdot\vec{E}|v,\vec{k} >|^2$ between the conduction band "*c*" and the valence band "*v*", where *v* stands either for *hh* or *lh* denoting heavy-hole and light-hole, respectively, is proportional to $1 \mp P_2(\cos\theta)$, where "-" gives the contribution due to the hh-c transition and "+" that of the lh-c transition. P_2 is the second degree Legendre polynomial. Not given in [8] are the proportionality factors which depend only on the modulus of $\vec{k}$ and the details of the optical excitation such as the amplitude, duration, and center-frequency of the optical excitation field $\vec{E}$. In our analysis, we proceeded quasi-phenomenologically and used prefactors which correspond to an optical excitation process in which the distribution function reflects the spectral shape of the optical pulse which we take to be Gaussian. In the context of a third-order approximation of the semiconductor Bloch equations without Coulomb interaction, this can be achieved in an approximate way, if, in the time-derivative of the distribution function, the interband polarization function is always taken at times long after the pulse. This procedure yields

Gaussian distribution functions centered at the carrier momentum that corresponds to the resonance condition of the excitation field: $\hbar\omega_0 = \varepsilon_k^e + \varepsilon_k^a$ with $a = hh, lh$. Here, ω_0 is the center frequency of the light pulse, $\varepsilon_{\bar{k}}^e = \hbar^2 k^2 / 2m_e + E_G$ is the electron energy with effective mass m_e, E_G, is the bandgap energy, $\varepsilon_{\bar{k}}^{hh} = \frac{\hbar^2 k^2}{2m_o}(\gamma_1 + 2\gamma_2)$ is the heavy-hole energy with Luttinger parameters γ_2 (m_0 is the electron mass in vacuum) and $\varepsilon_{\bar{k}}^{lh} = \frac{\hbar^2 k^2}{2m_o}(\gamma_1 + 2\gamma_2)$ is the light-hole energy. Our initial distribution, therefore, contains two contributions with slightly different center-momenta (due to the mass difference of hh and lh) and different angle characteristics because the hh has an angular momentum quantum number of $j = \pm 3/2$ (with respect to the quantization axis given by $\vec{k}$), whereas the lh has $j = \pm 1/2$:

$$f(\vec{k},0) = A_{hh}(k)\frac{1}{2}[1 - \cos^2\theta] + A_{lh}(k)\frac{1}{6}[1 + 3\cos^2\theta] \tag{11}$$

with

$$A_a(k) = A_0 \exp\left(-\left(\hbar\omega_0 - \varepsilon_k^e - \varepsilon_k^a\right)^2 / \left(2\gamma^2\right)\right), \tag{12}$$

where $A_0 = \left(\mu_0\, \mathcal{E}_0\right)^2 \frac{\pi}{2_\gamma{}^2}$, μ_0 is the angle-independent part of the interband dipole moment, $\mathcal{E}_0$ is the peak light-field amplitude and the width of the distribution is related to

the pulse duration τ (FWHM of intensity) through $\gamma^2 = \hbar^2 2\ln 2/\tau^2$. This approach, in which the light-field parameters enter only into the shape of the initial distribution, is strictly justified only if the relaxation processes are much slower than the light-pulse duration τ.

The numerical solutions of the initial value problem were obtained with algorithms similar to the ones discussed above in the context of the coherent anisotropic semiconductor Bloch equations. The algorithms were the same as those used in Ref. [9]. The maximum k-value (in each Cartesian direction) was chosen to be between 6.3 and 8.7 in units of a_B^{-1} (where a_B is the exciton Bohr radius of the systems, which is here $a_B = 132\,\mathring{A}$) and the number of k-points in each direction was between 43 and 59. Within this parameter range, the results were found to be insensitive to the parameters.

The solutions revealed the unexpected result that the anisotropy, measured by the quadruple moments of the distribution function in momentum space, decays slower than the zone-center occupation $f(0,t)$, which is a measure for the monotonicity of the distribution function in momentum space, increases. Further discussion can be found in Ref. [J3].

Finally, we turn to the topic which was designed to lay the foundation for a future application of the microscopic theories discussed above to the technology-oriented field of micro-cavity lasers and VCSELs. This work was partly motivated by the fact that the understanding of the polarization characteristics of the VCSEL output requires a detailed knowledge of the vectorial eigenmodes of the empty cavity. The understanding of the

vectorial mode structure provides the proper basis in which one can expand the light field when modeling running VCSELs. This, in turn, should enable the understanding of the experimentally observed coexistence and switching between transverse modes [10-18].

One goal of this project was to provide a general as well as an approximate analytical method to analyze the modal structure of VCSELs taking into account their polarization properties. For clarity, we focused on the idealized system of cold-cavity modes, i. e., we assumed all refractive indices to be real, and, therefore, the absence of gain and absorption from the system. In the cold-cavity configuration, the only information about the electromagnetic modes of VCSEL structures can be obtained from their reflectivity spectra, which was also calculated.

The general approach was to apply the knowledge of electromagnetic hybrid modes in optical fibers and, based on these modes, develop a generalized vectorial transform matrix method to allow for a three-dimensional solution of Maxwell's equation in cylindrical symmetry. The starting point, therefore, is

$$\vec{\nabla} \times \vec{E} = -i\frac{\omega}{c}\sqrt{\frac{\mu_0}{\varepsilon_0}}\vec{H} \text{ and}$$

$$\vec{\nabla} \times \vec{H} = i\frac{\omega}{c}\sqrt{\frac{\varepsilon_0}{\mu_0}}n_\ell^2\vec{E}\,, \tag{13}$$

where $c = 1/\sqrt{\varepsilon_0\mu_0}, \varepsilon_0$, and μ_0 are speed of light, electric and magnetic field permeabilities of a free space, respectively, n_ℓ is the refractive index of the corresponding dielectric layer, $\ell = 0,1,..N+1$. In cylindrical coordinates, the field components are $\vec{E} = \left(E_{\tau,} E_\varphi E_Z\right)$ and $\vec{H} = \left(H_\tau, H_\varphi H_Z\right)$. We assume that the solution of Eqs. (13) is of the general form $\vec{E}(r)\varnothing(z,\varphi)$ and $\vec{H}(r)\varnothing(z,\varphi)$, where $\varnothing(z,\varphi) = e^{-i\gamma\ell z}e^{-im\varphi}$, with $\gamma\,\ell$ being the $z-$component of the wave vector, and m being an integer describing the mode properties in azimuthal direction. The general solutions can be found in textbooks on fiber optics, and they are also listed in Ref. [J4]. The conditions of continuity at the VCSEL radius r=R yields the well-known dispersion relation of the hybird modes

$$\left(\frac{n_3^2}{\beta^2}\frac{J'_m}{J_m}+\frac{1}{\delta^2}\frac{K'_m}{K_m}\right)\left(\frac{1}{\beta^2}\frac{J'_m}{J_M}+\frac{1}{\delta^2}\frac{K'_m}{K_m}\right)=\frac{m^2}{R^2}\frac{k_z^2}{k_0^2}\left(\frac{1}{\beta^2}+\frac{1}{\delta^2}\right)^2, \tag{14}$$

where $J_m \equiv J_m(\beta R)$ and $K_m \equiv K_m(\delta R)$ are Bessel functions evaluated at the boundary, and the transverse propagation constants are given by

$$\beta = \sqrt{k_0^2 n_3^2 - k_z^2} \tag{15}$$

inside and

$$\delta = \sqrt{k_z^2 - k_0^2}\,. \tag{16}$$

outside the active layer of the VCSEL. The active layer has the layer number $\ell = 2N_L + 1$ and we denote $\beta_{2N_L+1} = \beta$ and $\gamma_{2N_L+1} = k_z$.

The transverse components of the electric and magnetic field in the ℓ – th layer may be expressed as a superposition in a complete set of orthogonal modes of the corresponding cylindrical waveguide as

$$\vec{\mathcal{E}}_T^{\ell} = \sum_{\nu} \vec{\mathcal{E}}_{\nu T}^{\ell} \qquad \text{and} \qquad \vec{H}_T^{\ell} = \sum_{\nu} \vec{H}_{\nu T}^{\ell}, \tag{17}$$

with

$$\vec{\mathcal{E}}_{\nu T}^{\ell} = \left(\mathrm{A}_{\ell}^{\nu +} e^{-i\gamma_{\ell}^{\nu} z} - \mathrm{A}_{\ell}^{\nu -} e^{i\gamma_{\ell}^{\nu} z} \right) \vec{E}_{\nu T}^{\ell}(\tau, \varphi), \tag{18}$$

$$\vec{H}_{\nu T}^{\ell} = \left(A_{\ell}^{\nu +} e^{-i\gamma_{\ell}^{\nu} z} + A_{\ell}^{\nu -} e^{i\gamma_{\ell}^{\nu} z} \right) \vec{H}_{\nu T}^{\ell}(\tau, \varphi), \tag{19}$$

where the subscript "T" stands for transverse field component. Here, we have explicitly written the forward and backward waves and the vectors $\vec{\mathcal{E}}_{\nu T}^{\ell}(\tau, \varphi)$ and $\vec{H}_{\nu T}^{\ell}(\tau, \varphi)$ are defined by comparing Eqs. (17) with the full definition of the transverse field components given in Table I and II of Ref. [J4]. Using the appropriate boundary conditions at the interface between two layers (say ℓ and $\ell + 1$), we obtain the final vectorial transform matrix formulation, which relates the amplitudes of the forward and backward running waves of each hybrid mode in adjacent layers,

$$\begin{pmatrix} \vec{A}^-_{\ell+1} \\ \vec{A}^+_{\ell+1} \end{pmatrix} = \overline{M}_\ell \begin{pmatrix} \vec{A}^-_\ell \\ \vec{A}^+_\ell \end{pmatrix} \text{ with } \overline{M}_\ell = \begin{matrix} \overline{M}^{--}_\ell & \overline{M}^{-+}_\ell \\ \overline{M}^{+-}_\ell & \overline{M}^{++}_\ell \end{matrix}, \tag{20}$$

where $\overline{M}_\ell$ is the transform matrix at the $z = z_\ell$.

In order to simplify the notation in Eq. (20), we introduced vectors ($\vec{A}^\pm_\ell$ and $\vec{A}^\pm_{\ell+1}$) and matrices $\left(\overline{M}^{\pm\pm}_\ell\right)$ with elements given by

$$\vec{A}^\pm_\ell = \left(\left\{A^{\nu\pm}_\ell\right\}\right)^T, \vec{A}^\pm_{\ell+1} = \left(\left\{A^{\mu\pm}_{\ell+1}\right\}\right)^T, \tag{21}$$

$$\left\{\overline{M}^{\pm-}_\ell\right\}\mu\nu = \mp \frac{Q^{\ell\ell+1}_{\nu\mu}}{\gamma^\mu_{\ell+1} \pm \gamma^\nu_\ell} e^{i\left(\gamma^\nu_\ell \pm \gamma^\mu_{\ell+1}\right)z\ell}, \tag{22}$$

$$\left\{\overline{M}^{\pm+}_\ell\right\}\mu\nu = \pm \frac{Q^{\ell\ell+1}_{\nu\mu}}{\gamma^\mu_{\ell+1} \mp \gamma^\nu_\ell} e^{-i\left(\gamma^\nu_\ell \mp \gamma^\mu_{\ell+1}\right)z\ell}, \tag{23}$$

where the superscript "T" indicates transposed vector and

$$Q^{\ell\ell+1}_{\nu\mu} = \frac{1}{2}\sqrt{\frac{\varepsilon_0}{\mu_0}} k_0\left(n^2_{\ell+1} - n^2_\ell\right) \frac{\int A_\ell dA_\ell \vec{E}^\ell_\nu(\tau,\varphi) \cdot \vec{E}^{\ell+1}_\mu(\tau,\varphi)}{\int_{A_\ell} dA_\ell \left[\vec{E}^{\ell+1}_\mu(\tau,\varphi) \times \vec{H}^{\ell+1}_\mu(\tau,\varphi)\right] \cdot \hat{z}}, \tag{24}$$

with A_ℓ denoting the transverse cross-section at the $z = z_\ell$ plane.

Finally, multiplication of the transform matrices $\overline{M}_\ell$ for all interfaces leads to the total transfer matrix of the VCSEL structure

$$\overline{M} = \prod_{\ell=0}^{N} \overline{M}_\ell \, . \tag{25}$$

In order to determine the eigenmodes of the VCSEL cavity, we note that in the running laser only the outcoming amplitudes are nonzero, that is $\vec{A}_{\overline{N}+1} = 0$ and $\vec{A}_0^+ = 0$. Therefore, the condition for the cavity eigenmode has the form: $\overline{M}^{--}\vec{A}_0^- = 0$ or, equivalently, det $\overline{M}^{--} = 0$, where $\overline{M}^{--}$ is a submatrix of the total matrix $\overline{M}$ (see Eq. 20). The solution of this condition yields resonant wavelengths, threshold gain and eigenmode profiles for the VCSEL cavity.

There are great advantages to such an almost analytical solution of Maxwell's equations, especially for the future project of developing a comprehensive microscopic model of the laser operation of VCSELs. Since the microscopic models for the nonlinear optical behavior and optical gain characteristics of the active layers require extensive numerical resources, the semi-analytical solution of the corresponding electromagnetic problem is needed to keep the problem numerically feasible. But the use and applications of the vectorial transform matrix approach does not require the targeted full microscopic model. Much information about the dependence of laser threshold and resonant

wavelengths can already be obtained from the electromagnetic model alone, as discussed for example in Ref. [J4].

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Publications Resulting from this Project

Publications in Peer-Reviewed Journals

J1 R. Binder and S.W. Koch, "Nonequilibrium Semiconductor Dynamics", Prog. Quant. Electr. 19, 307-462 (1995)

J2 G. Mohs, R. Binder, B. Fluegel, H. Giessen, and N. Peyghambarian, "Phonon-Induced Spectral Holes in the Gain Region of an Inverted Semiconductor", J. Opt. Soc. Am. B 13, 1298 (1996)

J3 R. Binder, H.S. Köhler, M. Bonitz, and N. Kwong, "Green's Function Description of Momentum Orientation Relaxation of Photo-Excited Electron Plasmas in Semiconductors", Phys. Rev. B 55, 5110 (1997)

J4 D. Burak and R. Binder, "Cold-Cavity Vectorial Eigenmodes of VCSELs", IEEE J. Quant. Elect., in press

J5 R. Binder, "Ultrafast Excitonic Nonlinear Birefringence in Anisotropic Semiconductor Quantum Wells", Phys. Rev. Lett., in press

Contributions in Peer-Reviewed Conference Proceedings

C1 R. Binder, H.S. Köhler, and M. Bonitz, "Memory Effects in the Momentum Orientation Relaxation of Optically Excited Plasmas in Semiconductors", paper QThA4, Quantum Electronics and Laser Science Conference (QELS '96), Anaheim, California, June 2-7, 1996

C2 G. Mohs, R. Binder, B. Fluegel, H. Giessen, and N. Peyghambarian, "Phonon Emission By Nonequilibrium Carriers in the Gain Region of an Inverted Semiconductor", paper QThB4, Quantum Electronics and Laser Science Conference (QELS '96), Anaheim, California, June 2-7, 1996

C3 G. Mohs, B. Fluegel, H. Giessen, and N. Peyghambarian, and R. Binder, "Phonon-Induced Spectral Holes in the Gain Region of an Inverted Semiconductor" International Conference on Physics and Simulation of Optoelectronic Devices IY, OE/LASE '96, San Jose, California, 29 January - 2 February 1996 (SPIE Proceedings Vol. 2693)

C4 D. Burak and R. Binder, "Electromagnetic Eigenmodes of Microdisk Resonators", paper QThF17, Quantum Electronics and Laser Science Conference (QELS '96), Anaheim, California, June 2-7, 1996

C5 D. Burak and R. Binder, "Theoretical Study of Electromagnetic Eigenmodes of VCSELs", International Conference on Physics and Simulation of Optoelectronic Devices V, OE '97, San Jose, California, 8-14 February 1997 (SPIE Proceedings Vol. 2994)

C6 R. Binder, "Theory of Ultrafast Optical Nonlinearities of Uniaxially Strained Quantum Wells" International Conference on Physics and Simulation of Optoelectronic Devices V, OE '97, San Jose, California, 8-14 February 1997 (SPIE Proceedings Vol. 2994)

C7 R. Binder, H.S. Köhler, N. Kwong, and M. Bonitz, "Theory of Momentum Orientation Relaxation in Semiconductors", International Conference on Physics and Simulation of Optoelectronic Devices V, OE '97, San Jose, California, 8-14 February 1997 (SPIE Proceedings Vol. 2994)

C8 R. Binder, "Nonlinear Excitonic Birefringence in Anisotropic Semiconductor

Quantum Wells", paper QTuE21, Quantum Electronics and Laser Science Conference (QELS '97), Baltimore, Maryland, May 18-23, 1997

HIGH POWER CIRCULAR-GRATING SURFACE-EMITTING LASERS

Mahmoud Fallahi

Objectives:

Investigate issues to the high power operation of circular-grating surface-emitting DBR (CG-SE-DBR) lasers.

The effect of grating positioning and aspect ratio on the lasing performance (threshold and output power).

Fabrication of high power CG-SE-DBR lasers on InGaAs/GaAs multi-quantum-well structure.

Status of Effort:

Circular-grating surface-emitting DBR lasers are very attractive for high power application. Because of their two dimensional nature, the position control and uniformity of the circular gratings are the key factors in low threshold high power operation of the lasers. The inclusion of a thin GaAs etch-stop layer in the top AlGaAs cladding layer for position control resulted in the lowest threshold current for CG-SE-\DBR lasers ever reported. A threshold current less than 20 mA and a pulsed output power in excess of 170 mW is successfully demonstrated. This also resulted in a reproducible operation of the lasers across the wafer. The laser operated under CW pumping with the same threshold current but the output power saturated around 7.5 mW caused by a poor heat sink.

Technical Summary:

There is a growing interest in low divergence, stable single-mode, high-power surface-emitting lasers for various applications. Among the potential devices, circular-grating surface-emitting DBR lasers are attractive candidates to provide single mode, low-divergence, high-power surface emission. Because of the two dimensional nature of these lasers, the position control and the uniformity of circular gratings are the key factors. The addition of an etch-stop layer in a strained multiple quantum wells (MQW) structure is an efficient solution allowing both the use of the same structure for the active and passive sections as well as an accurate positioning for the grating. In this work we

successfully fabricated low threshold current and high-power operation of an electrically pumped CG-SE-DBR laser using a strained triple-quantum-well (TQW) structure with an etch-stop layer.

Fig. 1 shows a schematic sectional view of the device. Similar to the case of linear grating-coupled DBR lasers, the two major parameters to be considered in the design of the CG-DBR lasers are the power coupling efficiency between the gain region and the grating region (C_o) and the coupling coefficient (κ) between the inward- and outward propagating waves. For a four layer structure they can be defined as follow [5]:

$$C_o = \left| \int_{-\infty}^{\infty} Z_a Z_g dz \right|^2 \tag{1}$$

and

$$\kappa = \Gamma_g \left(\frac{k_o^2}{2\beta} \right) \frac{\varepsilon_{clad} - \varepsilon_{cover}}{\pi m} \sin\left(\pi m \frac{w_g}{\Lambda} \right) \tag{2}$$

where Z_a and Z_g are the field distribution for the active and grating sections in the z direction, k_o is the wave number of light in vacuum, β is the propagation constant of the unperturbed waveguide, m is the grating order, ε_{clad} and ε_{cover} are the permittivity of the cladding layer and the cover layer (air in our case) respectively. w_g is the width of the grating valley. Γ_g is the overlap integral given by:

$$\Gamma_g = \int_{grat} |Z|^2 dz \; / \int |Z|^2 \, dz \tag{3}$$

The eigenvalue equation for the threshold condition can be approximated as:

$$C_o \rho_o \rho_{R1} e^{-j\Omega} e^{2\alpha R1} = 1 \tag{4}$$

ρ_o is the reflection coefficient at r = 0 and is defined as the ratio between outward-propagating to the inward-propagating waves. ρ_{R1} is the field reflection coefficient at r = R1. α represents the gain (or loss) and Ω is the total phase shift given by:

$$\Omega = \frac{\pi}{\Lambda} m(w_g + 2R_1) + 2(\beta_{gain} - \beta_{grat})R_1 \qquad (5)$$

For a CG-DBR as presented in fig.1, we have $\rho_O = 1$ while ρ_{R1} depends strongly on the coupling coefficient κ as follow:

$$\rho_{R1} = \frac{(-1)^n \kappa e^{-j2\delta R1} \sinh(\gamma L)}{\gamma \cosh(\gamma L) - (\alpha_g - j\delta)\sinh(\gamma L)} \qquad (6)$$

with

$$\gamma = \sqrt{\kappa^2 + (\alpha_g - j\delta)^2} \qquad (7)$$

where δ is the deviation from the Bragg frequency, L is the grating length, n is the order of the cylindrical waves and α_g is the loss in the grating region.

The above equations show that in order to reduce the threshold current, high coupling efficiency and coupling coefficient are needed. The use of the same layer structure for the gain section and grating section is a simple method of obtaining high coupling and eliminating the need for epitaxial regrowth. In this case, the value of coupling coefficient and power coupling efficiency are strongly influenced by the position of the grating (and cladding thickness).

Circular-grating surface-emitting DBR lasers similar to Fig. 1 are designed and fabricated. The layer structure is an InGaAs/GaAs strained TQW, graded-index, separate-confinement heterostructure (GRINSCH). A GaAs etch-stop layer is incorporated in the top cladding structure. The circular pumped region of the laser is placed in the center of the structure while the passive Bragg section surrounds the active section. Second order circular gratings with a radial extension of 150 μm were defined by an electron-beam system with polar coordinate writing capability.

The structure was grown by molecular beam epitaxy (MBE) on an n^+-GaAs substrate. The active region consists of three wells of 60 Å of $In_xGa_{1-x}As$ (x=20 %) separated by 300 Å GaAs barriers. This active region was sandwiched by graded $Al_xGa_{1-x}As$ layers. Top and bottom cladding consist of $Al_xGa_{1-x}As$ (x=67%) layers. A 150 Å GaAs etch-stop layer was grown in the top cladding layer, 0.2 μm above the graded region. A 60 μm diameter pumping region was defined by reactive ion etching (RIE) of

the top cladding layer in BCl_3:He down to about 0.2 μm above the etch-stop layer. Then the remaining AlGaAs was selectively etched down to the etch-stop layer in HF solution. Next 500 Å of SiO_2 was evaporated on the structure.

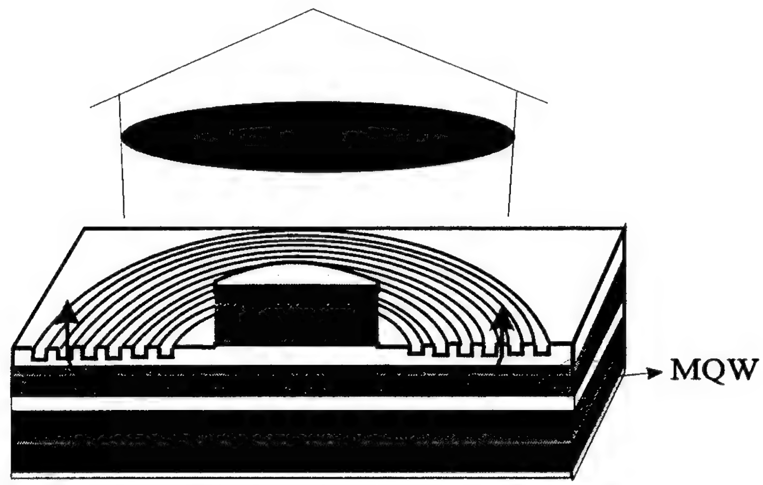

Fig. 1 : Schematic view of a CG-SE-DBR laser

Concentric circular gratings were defined by electron-beam lithography in 0.25 μm PMMA resist [6]. The radial extent of the circular gratings surrounding the active region is about 150 μm. The grating was next transferred into the oxide by RIE in CF_4:O_2 . The gratings, patterned in the oxide, were then transferred into AlGaAs by RIE in BCl_3:He using oxide as a mask. Since the oxide is unaffected by the etch, a high aspect ratio and an optimized coupling coefficient can be achieved. Finally an n-contact was evaporated at the back of the sample and the contacts were annealed.

The measurements were done at room temperature. The lasers were characterized under pulsed and continuous wave (cw) operation. The threshold current is less than 20 mA for both cases. The external quantum efficiency was as high as 14 %. An output power in excess of 170 mW without saturation under pulsed operation was obtained. The cw operation showed no change in the threshold current but the output power saturated at about 7.5 mW for a 150 mA current most probably due to the relatively high resistivity of the p-cladding layer and poor heat-sinking The lasing wavelength was measured to be

about 980 nm. Fig. 2 shows the lasing spectrum of a CG-SE-DBR laser at 2 times the threshold current. Single-mode operation at low injection and a mode hopping at high injection were observed.

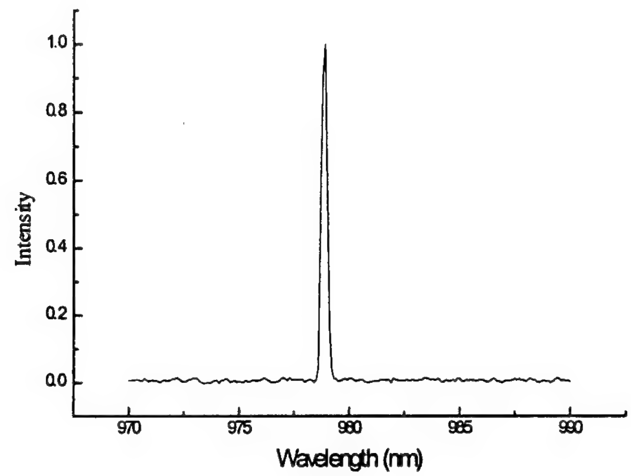

Fig. 2 : Lasing

spectrum of a CG-SE-DBR laser at $2I_{th}$

We measured a farfield divergence angle of less than 2 degrees in all directions with a quasi-circular cross section. At high-power operation, some of the lasers showed a multi-lobe far field pattern with a total divergence angle as high as 4.5 degrees, due to the multi-mode operation of those lasers. These results indicate the great potential of circular-grating surface-emitting DBR lasers for high power applications. In addition since no cleaved-fact is required, a 2-D array of these lasers can be fabricated.

Personnel Supported

One graduate student:
Scott Penner

Publications

1. M. Fallahi, N. Peyghambarian, K. Kasunic, M. Dion, Z. Wasilewski, "Circular Grating Surface-Emitting DBR Laser Array for Free-Space Applications," Electronics Letters, vol. 32, p. 1583, 1996.

2. M. Fallahi, M. Dion, Z. Wasilewski, M. Buchanan, M. Nournia, J. Stapledon and R. Barber, "Performance Improvement of Circular-Grating Surface-Emitting DBR Lasers Using a MQW Structure with Etch-Stop Layer," Electron. Lett., vol.31,No. 18, p. 1581, 1995.

3. K. Kasunic, M. Fallahi, E.M. Wright, "Gain and Index Saturation in Circular-grating Distributed-Feedback Semiconductor Lasers" to appear in the SPIE proceedings, 1997.

Interactions/Transitions

1. M. Fallahi, "Recent Developments on Circular-Grating Surface-Emitting DBR Lasers," IEEE Guest Speaker, Waves & Devices Chapter Phoenix Section, , Phoenix, Oct. 26, 1995.

2. M. Fallahi, N. Peyghambarian, M. Dion "Circular-grating DBR Lasers for High Power Surface Emission,"Ninth Annual Diode Laser Technology Review Conference, Albuquerque, NM, April 1996.

New Discoveries:

None

ATOM TRAPPING IN FAR-OFF-RESONANT OPTICAL LATTICES

Poul Jessen

Introduction.

The AC Stark shift (light shift) arising in laser interference patterns can be used to create stable periodic potentials for neutral atoms. Under appropriate conditions these "optical lattices" will laser cool and trap atoms in individual optical potential wells, with center-of-mass motion in the quantum regime. Experiments have explored a large number of lattice configurations in one, two and three dimensions, and have used a variety of techniques, including probe absorption and fluorescence spectroscopy, phase conjugation and Bragg scattering, to gain detailed insight into the dynamics of cooling and trapping [1]. In particular, it has been demonstrated that atoms are readily localized deep in the Lamb-Dicke regime. This suggests that it is worthwhile to pursue resolved-sideband Raman cooling [2] and quantum state preparation [3], by employing techniques similar to those recently demonstrated for trapped ions.

In an optical lattice formed by near-resonance light, control of the center-of-mass motion is limited by laser cooling and heating processes that occur at a rate determined by photon scattering. These dissipative processes can be avoided if the lattice is formed by intense light tuned far from atomic transition. Such far-off-resonance lattices have been used extensively in atom optics as diffraction gratings and lenses [4], and recently as model systems in which to study quantum chaos [5] and quantum transport [6]. The research supported by this grant has studied the use of far-off-resonance optical lattices to

trap neutral atoms in the Lamb-Dicke and quantum regime, and in an environment essentially free of dissipation. A key goal has been to evaluate the feasibility of resolved-sideband Raman cooling and coherent control of the atomic center-of-mass motion.

Summary of Research

1. Demonstration of a far-off-resonance optical lattice for Cesium atoms

An important accomplishment, and a prerequisite for much of the research discussed below, was our demonstration of Cesium atom trapping in a 1-dimensional (1D) far-off-resonance optical lattice. The lattice was formed using a 0.5 W semiconductor laser tuned anywhere between 5 and 40 GHz below the Cs $6S_{1/2}(F=4) \rightarrow 6P_{3/2}(F'=5)$ transition at $\lambda = 852$ nm.

2. Loading scheme for deeply bound states of a far-off-resonance optical lattice.

When atoms are trapped in a far-off-resonance optical lattice, the absence of built-in laser cooling makes it difficult to obtain vibrational excitation and confinement comparable to the near-resonance case [7]. This in turn makes sideband cooling schemes, as well as related means of coherent control, considerably less efficient. A key part of our research has therefore been the development of a loading scheme to overcome this limitation [8]. Our technique relies on adiabatic transfer of Cesium atoms, initially cooled and trapped in a near-resonance lattice, into a superimposed far-off-resonance lattice. If truly adiabatic transfer can be accomplished, then the net result will be a one-to-one

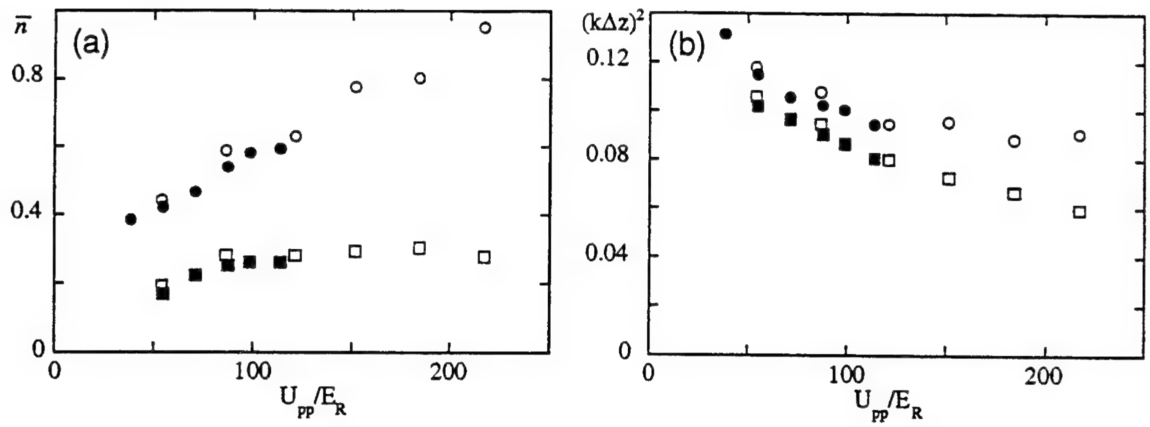

Fig. 1. (a) Mean vibrational excitation $\bar{n}$ in the far-off-resonance lattice, as a function of the peak-peak modulation depth U_{pp} of the lattice potential. Solid (open) symbols indicate data taken for lattice detunings of Δ = -20 GHz (Δ = -10 GHz). Circles (squares) indicate vibrational excitation measured at $\tau = 20$ ms ($\tau = 0.1$ ms) after transfer from the near-resonance lattice. (b) Lamb-Dicke parameter $(k\Delta z)^2$ corresponding to the data in (a).

transfer of atoms between bound states of the two lattices. Immediately following transfer we do in fact achieve trapping parameters comparable to the near-resonance case, with a mean vibrational excitation as low as $\bar{n} \approx 0.3$ (consistent with no vibrational heating during transfer), and a typical rms position spread of $\Delta z \approx \lambda/20$ (fig. 1). Transfer efficiency between the near-and far-off-resonance lattices is typically in the range 90-95%. A small bias field applied while atoms are cooled and trapped in the near-resonant lattice allows us to skew the distribution of population towards one of the magnetic sublevels $|m = \pm 4\rangle$, as discussed in more detail below. A small bias magnetic field, applied during transfer, helps maintain the atomic orientation. With those minor modifications of the loading scheme we can preferentially populate a specific magnetic- and vibrational ground state of the far-off-resonance lattice.

3. Trapping dynamics in a far-off-resonance optical lattice.

Photon scattering constitutes a major source of heating for atoms trapped in an optical lattice. Fig. 2 shows the increase in mean vibrational excitation $\bar{n}$, as a function of trapping time τ, measured for lattices of different depth and detuning [8]. Initially $\bar{n}$ increases roughly as expected from photon scattering; fig. 2 shows calculations of $\bar{n}$ vs. time, obtained by solving rate equations for the vibrational populations for an atom bound in an optical potential well on the axis of the lattice beams. Note that one would expect the rate of heating to increase with photon scattering rate, a behavior which we observe only during the first few ms. At later times $\bar{n}$ depends only on the lattice depth. Fig. 1a illustrates this linear scaling of $\bar{n}$ with lattice depth, at $\tau = 20\,\text{ms}$. The observed behavior is qualitatively similar to the steady state scaling known from near-resonance lattices [1], and one might speculate that a cooling mechanism is active also in the far-off-

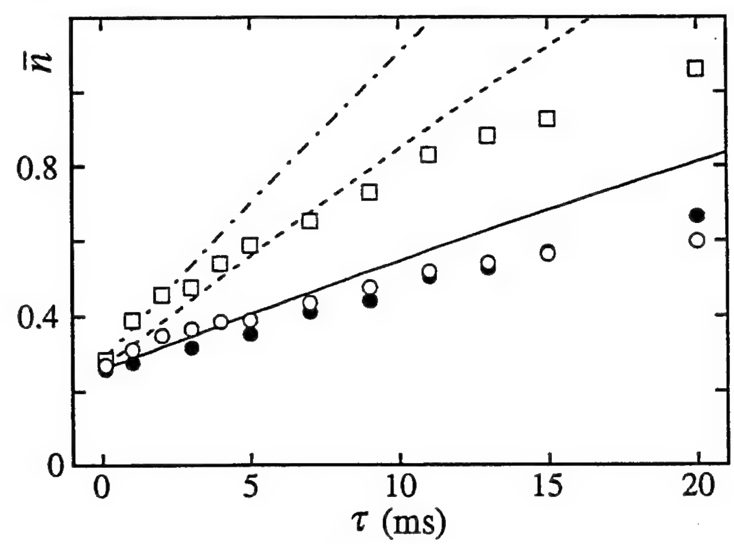

Fig. 2. Mean vibrational excitation $\bar{n}$ in the far-off-resonance lattice, as a function of time τ elapsed since transfer from the near-resonance lattice. Solid circles correspond to a lattice detuning $\Delta = -20$ GHz ($-3831\,\Gamma$) and a peak-peak modulation depth $U_{pp} = 105 E_R$ of the potential. Open symbols correspond to $\Delta = 10$ GHz ($-1916\,\Gamma$) and $U_{pp} = 105\,E_R$ (circles), $U_{pp} = 209\,E_R$ (squares). Solid, dashed and dot-dashed lines show the expected heating from photon scattering.

resonance case. Unfortunately the measurement uncertainties and limited interaction time imposed by our 1D geometry does not permit us to confirm or rule out whether a steady state will eventually be reached.

It is possible that the increase in $\bar{n}$ is limited by the escape of atoms with a thermal energy above the lattice potential well depth. We find that the number of atoms trapped in the lattice decays exponentially, with a time constant $\tau_0 \approx 2\,(\mathrm{ms/GHz}) \times \Delta$. This scaling is consistent with loss caused predominantly by the escape of hot atoms. An atom trapped in a potential well of depth U_{pp} is heated at a rate proportional to the photon scattering rate γ_s, and will escape after a time proportional to $U_{pp}/\gamma_s E_R \propto \Delta/\Gamma$. Here $E_R = (\hbar k)^2/2M$ is the photon recoil energy, and $\Gamma = 2\pi \times 5.22\,\mathrm{MHz}$ is the natural linewidth. Other loss processes that we expect to contribute are optical pumping to the F=3 hyperfine ground state, and, at long trapping times, escape in the direction perpendicular to the lattice axis.

An important result, following from our study of trapping dynamics, is the conclusion that resolved-sideband Raman cooling and quantum state control appears to be feasible in principle. Sideband cooling can remove a quantum of vibration every few oscillation periods; this time must be much less than the time required to pick up a quantum of vibration due to all sources of heating. For the lattice parameters explored in fig. 2, the most rapid rate of increase in $\bar{n}$ occurs immediately after transfer; it is approximately $20\,\mathrm{s}^{-1}$, $40\,\mathrm{s}^{-1}$ and $\sim 100\,\mathrm{s}^{-1}$ for the 3 sets of data. At the same time the

vibrational oscillation frequency in the harmonic approximation is 42 KHz and 60 KHz, for lattice

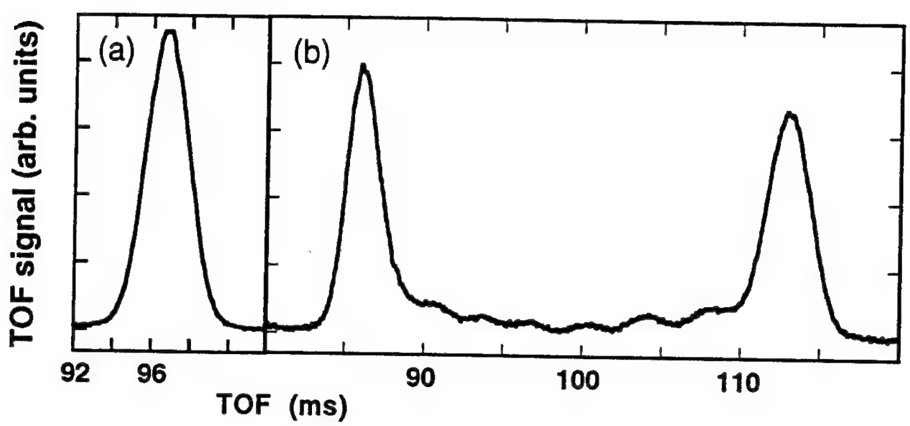

FIG. 3. (a) Typical time-of-flight distribution observed in a simple time-of-flight measurement. The corresponding momentum distribution is indistinguishable from a Gaussian. (b) Time-of-flight distribution in the presence of a gradient magnetic field. Each of the 9 peaks correspond to atoms in a separate magnetic sublevel.

depths of $105\,E_R$ and $209\,E_R$ respectively. The increase in $\bar{n}$ during an oscillation period thus falls in the range 0.5×10^{-3} to 2×10^{-3}, well into the regime where sideband cooling should be possible.

4. Stern-Gerlach/time-of-flight measurement of magnetic sublevel populations.

In order to fully understand laser cooling and trapping dynamics in near- and far-off-resonance optical lattices, one must characterize both the external (center-of-mass) and internal state of the atoms. To this end we have developed a new measurement technique, which yields independent values for the temperature and populations of atoms in each ground state magnetic sublevel.

Our technique is essentially a Stern-Gerlach version of the standard time-of-flight measurement, which is commonly used to obtain laser cooled atomic momentum distributions. Atoms are released from the optical lattice, and fall to a probe volume located directly below the lattice; as fall they experience a state dependent acceleration produced by a magnetic field gradient. The field gradient is sufficient strong to separate time-of-flight distributions corresponding to atoms in different magnetic sublevels (fig. 3). A simple version of this technique was first explored in ref. [9]; we have developed it into a precise measurement tool by (i) eliminating precession of the atomic spin through the addition of a homogeneous bias magnetic field at the time atoms are released from the lattice, and (ii) performing a detailed trajectory analysis in the 3-dimensional inhomogeneous magnetic field.

Polarization gradients of the light field in an optical lattice results in an entanglement of atomic internal and external degrees of freedom. We have, therefore, proposed that the above measurement of the atomic orientation can be used to determine

atomic positions with sub-wavelength resolution. Sub-wavelength position measurements will be a key

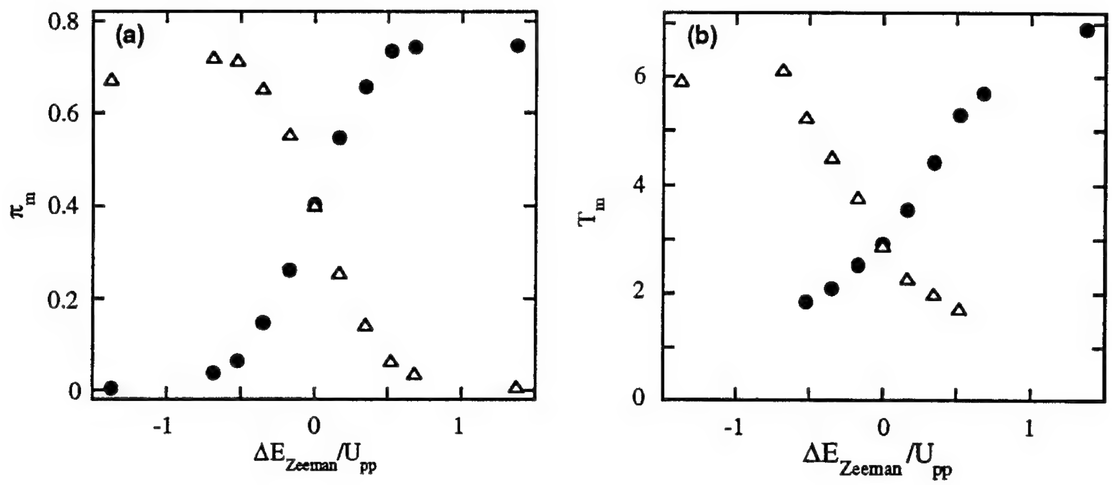

Fig. 4. (a) Populations π_4 (solid circles) and π_{-4} (open triangles) in the states $|m = \pm 4\rangle$, as function of the differential Zeeman shift between those states in units of U_{pp}. (b) Temperature of atoms in the states $|m = 4\rangle$ (solid circles) and $|m = -4\rangle$ (open triangles). The data was measured for a lattice with $U_{pp} = 140\, E_R$ and $\Delta = -20\,\Gamma$.

ingredient in a series of studies of macroscopic quantum tunneling in optical lattices, which we are planning in the near future.

5. Optimized state preparation in a near-resonance optical lattices.

Our research clearly demonstrates that a far-off-resonance optical lattice is best loaded with atoms by transfer from a superimposed near-resonance lattice. In this context, it becomes crucial to optimize the cooling process in the near-resonance lattice, so as to maximize the occupation of the desired magnetic- and vibrational ground state. We have performed a detailed study of the possibilities to enhance this initial state preparation, through the addition of weak magnetic fields. Our work shows directly how

a magnetic field parallel to the lattice quantization axis modifies both the kinetic temperature and the distribution of population among magnetic sublevels (fig. 4). Maximum population in one of the two stretched states $|m = \pm 4\rangle$ is found to occur when the differential Zeeman shift between those states is roughly equal to the modulation depth U_{pp} of the corresponding lattice potentials. We find a maximum stretched state population in the range $0.70 - 0.75$, achieved for lattice depths in the range $U_{pp} = 70 - 300\ E_R$, and a detuning $\Delta = -20\,\Gamma$.

Because atoms are trapped near the zero-point of motion, the degree of thermal excitation in the lattice is best described by a vibrational temperature. In the context of state preparation it is even more appropriate to calculate and quote the corresponding vibrational ground state population in the lattice potential wells. Fig. 5 shows the fraction of atoms found in the vibrational ground states of the potential wells corresponding to the stretched states, for a lattice modulation depth $U_{pp} = 70\ E_R$ and detuning $\Delta = -20\,\Gamma$.

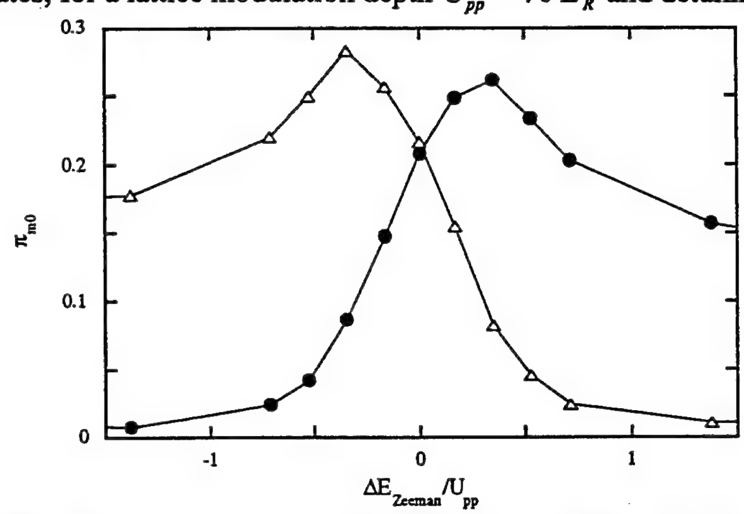

Fig. 5. Vibrational ground state populations π_{40} (solid circles) and π_{-40} (open triangles) in the stretched states $|m = \pm 4\rangle$. Lattice parameters are $U_{pp} = 70\ E_R$ and $\Delta = -20\,\Gamma$.

These are the lattice parameters that produce the absolute maximum values of ~0.3 for the populations. In the absence of any magnetic field, we find the vibrational ground state populations for the two stretched states to be equal, and to attain a maximum value of ~0.20, in excellent agreement with earlier theoretical work [10].

A magnetic field applied transverse to the lattice quantization axis affects laser cooling in a manner quite different from an axial field. In general, we find that the temperature of atoms in the stretched states shows a clear minimum for a non-zero transverse field; this minimum becomes even more pronounced in the presence of an axial field. The observed decrease in temperature is accompanied by a redistribution of population among magnetic sublevels, so that the net result is a *decrease* in the vibrational ground state populations of the lattice. We note that the existence of a global minimum in temperature for $\mathbf{B} \neq 0$ calls for caution if one attempts to cancel out background magnetic fields by minimizing the atomic temperature, as is commonly done in laser cooling experiments.

6. Resolved-sideband Raman cooling and quantum state selection.

We have initiated work on resolved-sideband Raman cooling, which we plan to implement using Raman transitions between magnetic sublevels, in a manner closely analogous to that demonstrated for single trapped ions [2]. To gain experience with Raman spectroscopy in a far-off-resonance lattice, we have explored a simple 1D version of such a scheme (fig. 6) [11]. A pair of laser beams, of opposite circular polarization and propagating along the lattice axis, are tuned to the "red" Raman sideband

$|m=4,n\rangle \to |m=2,n-1\rangle$. Relaxation back to the state $|m=4,n-1\rangle$ is provided by

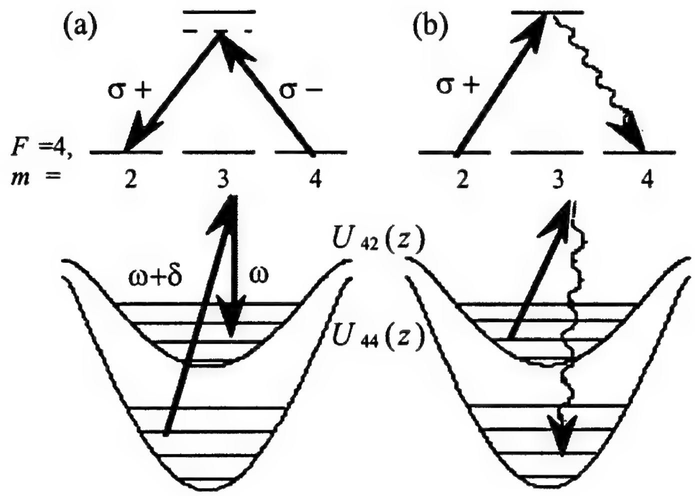

Fig. 6. Basic scheme for resolved-sideband Raman cooling. (a) external Raman beams, or Raman coupling intrinsic to the lattice, transfers population from state to state $|m=2,n-1\rangle$. (b) Optical pumping provides relaxation back to state $|m=4,n-1\rangle$, for a net loss of close to one quantum of vibrational excitation.

optical pumping. The Raman beams are detuned a few linewidths from the $F=4 \to F'=4$ transition, and have adjustable frequency difference δ. This is essentially the Raman cooling scheme examined theoretically in ref. [12].

We observe vibrational populations in the far-off-resonance lattice by adiabatic release of the atoms, followed by a measurement of the momentum distribution. Adiabatic release maps the n'th band onto the momentum interval $(n-1)\hbar k > p > n\hbar k$ [13], and the population of individual bands/vibrational states can therefore be directly measured. Fig. 7 compares momentum distributions, observed for δ detuned from or resonant with the $|m=4,n=0\rangle \to |m=2,n=0\rangle$ transition. It is clear that atoms have

been selectively removed from the $|m=4, n=0\rangle$ state, but have not reappeared elsewhere. We have not studied in detail how atoms are lost during Raman transition/optical pumping cycles, but it is highly probably that optical pumping to the $F = 3$ hyperfine ground state is responsible.

In order to minimize hyperfine optical pumping during sideband Raman cooling, it is essential to minimize population in the intermediate excited state. This is usually accomplished using far-off-resonance Raman beams. We have nearly completed a theoretical study of a new scheme for Raman sideband cooling, which relies on stimulated Raman coupling intrinsic to the lattice light field itself. A somewhat unexpected conclusion is that a destructive quantum interference between excited hyperfine states renders sideband Raman cooling at best marginally feasible, for alkali atoms trapped in any 1-dimensional lattice configuration. So far this conclusion is supported by our experimental efforts, which in the limit of far-off-resonance Raman coupling have failed to achieve either cooling or state selection. In a 2D or 3D geometry the situation appears much more promising. The extra degrees of freedom permit the introduction of a π-polarized component of the lattice field, and the resultant Raman coupling can be several orders of magnitude larger than in a comparable 1D far-off-resonance lattice [11]. We are currently studying this situation in detail. We

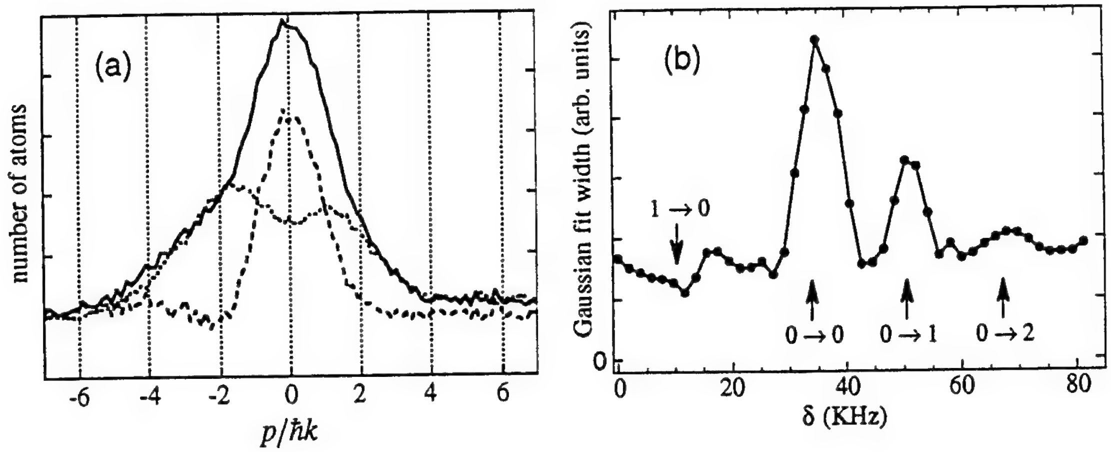

Fig. 7. (a) Momentum distributions measured after adiabatic release of atoms from the far-off-resonance lattice. The solid line and dotted lines show the momentum distribution, measured when the frequency difference δ of the Raman beams was detuned resp. resonant with the $|m=4,0\rangle \rightarrow |m=2,0\rangle$ transition. The dashed line is the difference between these distributions, and shows that population has been removed from the momentum interval $-\hbar k \leq p \leq \hbar k$, corresponding to the ground vibrational state. (b) Measure of the width of the momentum distribution, as a function of the frequency difference δ between the Raman beams. Arrows indicate the expected positions of the heating transitions $|m=4,0\rangle \rightarrow |m=2, n=\{0,1,2\}\rangle$, and the cooling transition $|m=4,1\rangle \rightarrow |m=2,0\rangle$.

have just initiated a 2D experiment; demonstrating resolved-sideband Raman cooling in this configuration is a top priority, and supported in part by a new JSOP grant for the period 1997-2000.

6. Tunneling and quantum control in bipotential wells.

A spin-off from our theoretical study of schemes for resolved-sideband Raman cooling, has been the discovery of a new and promising system in which to study quantum transport and quantum control. The system consists of Cs atoms trapped in a 1D far-off-resonance lattice, which consists of a series of double potential wells. Near

the two minima of each double-well, the local light polarization is predominantly σ+ and σ- respectively, so that bound states in these wells have mainly $m > 0$, respectively $m < 0$ character. One can then use a small axial magnetic field to tune the relative energy of bound states in the two wells, and thereby study both resonant and non-resonant macroscopic quantum tunneling. A measurement of the atomic magnetization will yield accurate information about the atomic position at any given time, and provide a direct means to observe tunneling. This will allow us to address experimentally the effect of dissipation in tunneling [14], in a simple system whose dynamics can be easily controlled and modeled via first-principle theory. The atom/double-well model system has obvious, interesting parallels to other mesoscopic quantum systems, such as quantum point contacts, SQUID's, Josephson junctions and small magnetic domains.

8. Two-dimensional annular laser trap.

Optical lattices are by no means the only configurations in which laser light can be used to create traps for neutral atoms. We have developed a theory of the two-dimensional motion of cold atoms in a near-resonant Laguerre-Gaussian laser beam [15]. For a red-detuned field the laser beam provides an annular light shift potential and the atomic motion divides into vibrational and rotational modes analogous to a two-dimensional molecule. In the ground vibrational state, this corresponds to a new realization of the two-dimensional rotator. We have illustrated the novel physics which may be explored with this system, by showing that gravity acts analogously to a static electric field applied to a charged rotator. We have also explored the possibility of

performing Raman spectroscopy of the bound states of the trap. Although it will pose a substantial experimental challenge, this spectroscopy is of considerable interest as it may permit the observation of new selection rules involving conservation of the total orbital angular momentum of the light and atoms, and may provide new insight into the concept of orbital angular momentum of light fields. We hope to extend this work also to laser traps formed by e. g. Bessel beams, in which case the trapping potential has cylindrical symmetry and is approximately periodic in the radial coordinate. The equivalent refractive-index structures for light waves have recently attracted great interest as distributed feedback resonators for microdisk semiconductor lasers.

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2. "Atom Trapping in Deeply Bound States of a Far-Off-Resonance Optical Lattice", D. L. Haycock, S. E. Hamann, G. Klose and P. S. Jessen, to appear in Physical Review A **55,** Rapid Communications, June 1997.

3. "Atom Trapping in the Lamb-Dicke regime in a far-off-resonance optical lattice", D. L. Haycock, S. E. Hamann, G. Klose and P. S. Jessen, Proc. SPIE **2995**, 163 (1997).

Articles in Preparation

1. "Laser Cooling in Shallow Optical Lattices and Weak Magnetic Fields", D. L. Haycock, S. E. Hamann, G. Klose, G. Raithel and P. S. Jessen.

2. "A Scheme for Quantum State Preparation and Control in Optical Lattices", P. S. Jessen and I. H. Deutsch.

Conference Presentations

1. "Laser Cooling and Trapping in Far-Off-Resonance Optical Lattices", D. L. Haycock, S. E. Hamann, G. Klose and P. S. Jessen, workshop on "Quantum Control of Atomic Motion", Albuquerque, New Mexico, 1-2 March 1997.

2. "Atom trapping in the Lamb-Dicke regime in a far-off-resonance optical lattice", D. L. Haycock, S. E. Hamann, G. Klose and P. S. Jessen, Photonics West, San Jose, California, 8-14 February 1997.

3. "Laser Cooling and Trapping in Far-Off-Resonance Optical Lattices", D. L. Haycock, S. E. Hamann, G. Klose and P. S. Jessen, workshop on "Optical Lattices", Les Houches, France, 27-31 January 1997.

4. "Quantum State Preparation in Optical Lattices", P. S. Jessen, and I. H. Deutsch, workshop on "Optical Lattices", Les Houches, France, 27-31 January 1997.

5. "Cooling to the Recoil Limit with an Optical Lattice", D. L. Haycock, S. E. Hamann, P. H. Pax and P. S. Jessen, CLEO/QELS 96, Anaheim, California, 2-7 June 1996.

6. "Adiabatic Release and Transfer of Cs Atoms from a Near-Resonant to a Far-Off-Resonant Optical Lattice", P. S. Jessen, D. L. Haycock, S. E. Hamann, 1996 meeting of the Division of Atomic and Molecular Physics of the American Physical Society, Ann Arbor, Michigan, 15-18 May 1996.

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PI, salary paid in part by this grant:

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G. Klose	Graduate Research Assistant

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SODIUM GUIDE STAR LASER

Richard C. Powell

Research Findings

Objective

The objective of this research is to develop a novel type of optically pumped solid state laser system for use as a sodium guide star laser in adaptive optics applications.

Status of Effort

This is a new project that was initiated three months ago. During this time, a system design concept has been developed and materials and components ordered to build a laboratory prototype.

Accomplishments

Adaptive optics is an important technology for military applications since it can provide diffraction-limited imaging from ground-based telescopes for satellite reconnaissance and diffraction-limited laser beam delivery telescopes for groundbased laser weapons. A "guide star laser" is one important component of adaptive optics technology. So far, the ideal laser system for generating sodium guide stars has not been developed. The research proposed here has the potential for developing an all solid state laser system with the operating characteristics required for sodium guide star applications.

The unique laser design proposed here utilizes nonlinear optics effects, such as intracavity solid state stimulated Raman shifting combined with second harmonic

generation to attain the appropriate operating wavelength. The special cavity design makes use of the four-wave mixing properties of stimulated Raman shifting to provide automatic quality enhancement of the beam. Optimized high-power pump and Raman laser resonator designs will be developed through computer modeling and prototype testing. The laser will be capable of efficiently producing the pulse and energy format required for a sodium guide star laser, or for a master oscillator to pump a power amplifier in order to attain the power levels required for guide star applications. Power scaling remains the major issue. This research will determine whether this laser system can operate by itself as a high-power guide star laser, or if it is better to use it as a seed laser to pump high-power amplifiers.

The baseline approach we propose is to frequency double the output of a high-power intracavity solid state Raman laser already developed in our laboratory for eye-safe lidar applications. Some innovative aspects of this technique include:

- Pump to 1st Stokes conversion efficiency ~ 90%;
- Dual crystal second harmonic generation (SHG) technique yields efficiencies of ~ 85%;
- Overall optical-to-optical efficiency ~ 77%;
- Diode pumping allows for excellent wall-plug efficiency and minimal cooling requirement;
- Compact, all-solid-state design is amenable to rugged environments;
- Excellent 1st Stokes beam quality (1.1 XDL) is obtained from a large mode-volume, highly multimode pump cavity designs, which are optimized for efficient energy extraction, due to intracavity Raman beam cleanup;
- "Cleaned up" 1st Raman laser output yields excellent SHG efficiency and second harmonic beam quality;
- SSRS has no angular, thermal of wavelength acceptance products so alignment is trivial and very large (~ 5 cm) crystals can be utilized to optimize the efficiency;
- Intracavity SSRS suppresses laser "spiking" in the long-pulse operation;
- Intracavity SSRS serves as an optical limiter to mitigate optically induced damage.

The Raman laser system will be designed according to the layout shown in Fig. 1. This involves two coupled cavities: the pump laser cavity and the Raman laser cavity. The pump laser cavity is designed for maximum energy extraction to improve the overall efficiency of the system. This is achieved by requiring the laser medium (slab or rod) to be the limiting aperture of the system. Intrinsic to large Fresnel number cavities is a near-field, highly multimode, intracavity spatial beam imprint. However, due to the mechanism of intracavity Raman beam cleanup, none of this higher order structure is transferred to the desired Stokes output.

The laser resonator design is based on a simple "L" - resonator with a waist located in the Raman medium as shown in Fig. 1. An acusto-optic modulator (AOM) is included to mode-lock the intracavity field. A dual prism scheme is utilized to adjust the cavity length to match the natural driving frequency of the particular AOM employed.

An intracavity etalon is placed in the pump laser cavity to confine the gain bandwidth to approximately 1.5 Ghz. By this restriction, we are guaranteed transform limited pulses of temporal width of 667 ps. Our proven dynamical computer models have established that 333 ps transform limited Raman pulses will ensue from these pump pulses when an appropriate output coupling is selected. This assures an output linewidth of 3 GHz, which matches the inhomogeneously broadened absorption bandwidth of a 200 K sodium layer. The output bandwidth can be tuned to match the varying diurnal thermal cycles of the sodium layer by a rotation of the intracavity etalon.

The central output frequency of the pump laser, and hence system output, can be tuned to the D2 resonance by injection seeding with a rapid tuned, commercially available, monolithic isolated single-mode, end-pumped ring laser (MISER). We propose locking the output frequency to the sodium layer D2 resonance by implementing a positive feedback servo-control-loop to the received backscatter.

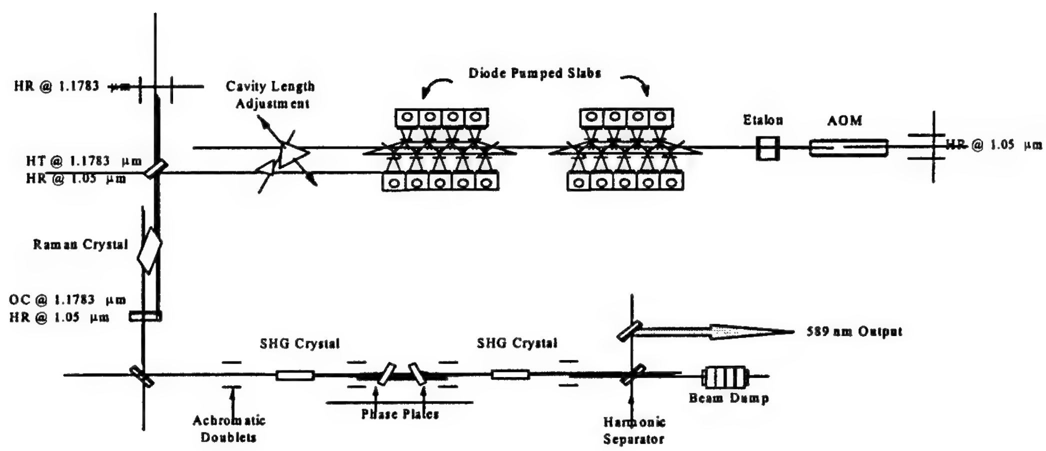

Figure 1. Raman sodium guide star laser system layout. The pump laser cavity and Raman laser cavity are coupled and share a common leg containing the Raman crystal. The pump laser cavity is an "L" - shaped cavity defined by two highly reflective (HR) mirrors at the pump wavelength. The Raman laser cavity is mode matched by judiciously selecting the position and radius of curvature of the end mirror. Frequency doubling of the Raman output radiation is performed in two steps for an overall pump to 589 nm efficiency of ~ 77%.

The Raman laser cavity shares a common leg with the pump laser cavity. The two cavities are coupled by a single dichroic mirror that acts as a high reflector (HR) for the pump wavelength and a high transmitter (HT) for the 1st Stokes wavelength. The mirror defining the independent Raman leg is set to mode-match the two cavities. The first fundamental mode of the Raman laser cavity is matched to the multimode beam radius of the pump laser cavity. As a result of intracavity Raman beam cleanup, the output of the Raman laser is guaranteed to be single mode.

Our calculations show that this system can be scaled to tens of Watts with the required pulse characteristics for sodium guide star applications. To reach a final system power of between 100 W and 1 kW will require further research and design considerations, and this is one of the major thrust areas of this proposal. Two possible options to be considered are using this system as a master oscillator to seed high power amplifiers, and developing new materials with higher damage thresholds. The current technology of power amplifiers of the type required for this system have achieved powers of over 100 W. Using materials such as lithium borate for the frequency doubler will significantly increase the optical damage threshold of the system.

There are two basic Nd laser host - Raman laser crystal combinations we propose to characterize in the feasibility study. Our baseline approach is based on Nd:YLF lasing at the 1.047 mm transition, shifted by a KNO_3 SSRS crystal. We have chosen as an alternative scheme a system based on Nd:YAG lasing at the 1.064 mm transition, shifted by a $CaWO_4$ SSRS crystal. Each of these schemes can produce a fundamental output of

1.1783 mm, which when doubled is resonant with the sodium layer D_2 resonance. The quantum efficiency of each scheme is ~ 90%, so very large conversion efficiencies are possible. Both SSRS materials are commercially available, and have superior optical quality. KNO_3 has very similar optical and SRS characteristics to $Ba(NO_3)_2$, which has been successfully power scaled. $CaWO_4$ has a relative low threshold for optical damage and special efforts will have to be made to achieve the required power scaling with this material. We feel this problem can be overcome through a combination of material improvements and system design (e.g. master oscillator-power amplifier configuration).

Because of the long pulse lengths required for efficient sodium excitation, the Raman laser radiation has a low peak, high average power. Efficient doubling of low-peak-power radiation requires long interaction length, large acceptance parameters, high damage threshold, and low absorption in the frequency doubling crystal. To achieve efficient doubling of low-peak-power radiation, a tight focus of the pump radiation into the nonlinear crystal is necessary to obtain high peak intensities. However, to achieve doubling efficiencies greater than 50%, the bandwidth of the focused pumps angular spectrum must be narrower than the phase-matching angular acceptance of the doubling crystal. This restricts the selection of doubling crystals and crystal cut geometries. A maximum angular acceptance parameter and zero beam walk-off is achieved when phase matching is possible in the crystallographic x-y plane, i.e. q = 90. In this geometry, the phase-matching becomes noncritical (NCPM) and a tightly focused beam can remain

phase-matched over very large interaction lengths. We are currently testing doped KTP that possess the capacity to double 1.1783 mm to 589.158 nm in the NCPM geometry.

Because all real optical beams have a finite angular spectrum, a dephasing occurs between the fundamental and second harmonic radiation that results in a "back-conversion" of the second harmonic to the fundamental. For an ideal Gaussian beam, this occurs when 60% of the fundamental have been converted into the second harmonic. To achieve conversion efficiencies greater than 60%, a relative phase shift of must be imparted between the two beams before further conversion can be accomplished. Several dual crystal - quadrature geometries that accomplish a degree of rephasing have been devised and have been demonstrated to yield doubling efficiencies > 80%.

The doubling technique we propose to use utilizes two counter-rotated phase plates between the two crystals to rephase the fundamental and second harmonic radiation. The relative phase shift required to maximize the SHG efficiency can be tuned by rotating the plates. The efficiency is independent of the pump drive and crystal lengths. Doubling conversion efficiencies of ~ 85% were demonstrated using this technique.

Scientific Personnel Supported

James Murray

Publications

None

Interactions/Transitions:

Collaborations with Air Force and Army Laboratories:

During this funding period, we have had site visit demonstrations for:

Steve Gottof and Cindy Swim of the **Army** *Edgewood Research, Development and Engineering Center*
Jay Fox of the **Army** *Night Vision Laboratory*
Christopher Clayton of the **Air Force** *Phillips Laboratory*
Ed Watson of the **Air Force** *Wright Laboratory.*

Each of these individuals has expressed significant interest in the laser technology being developed through this project.

Inventions/Patent Disclosures

All solid state guide star laser based on Raman shifting. (See attached form.)

Honors/Awards

None

ULTRA-SHORT PULSE PROPAGATION AND THE QUANTUM STATISTICS OF OPTICAL SOLITONS

Ewan M. Wright

Status of Effort

Current work in the general areas of nonlinear optics, in particular soliton propagation in quantum dot waveguides, two-dimensional motion of cold atoms, and Bose-Einstein condensation in small atomic samples are progressing well with significant recent progress. Highlights include a comprehensive analytical and numerical study of soliton propagation in quantum dot waveguides for wavelengths below the half bandgap, the theory of artificial two dimensional molecules formed from cold atoms trapped in annular laser beams, and the prediction of collapses and revivals of the macroscopic wavefunction for small atomic BECs.

Accomplishments

In the following paragraphs I will summarize recent accomplishments in the areas mentioned above.

We have recently been studying nonlinear pulse propagation in quantum dot waveguides for wavelengths below the half bandgap. The significance of this work stems from recent interest in the non-resonant nonlinearity which arises just below the half bandgap in semiconductors. These media, such as InGaAs, behave almost like Kerr media and have allowed for the fabrication and demsonstration of nonlinear optical switches (eg. directional coupler) which operate near to the ideal limit, with instantaneous response time. We have developed a unified theory of pulse propagation in the vicinity

of a two-photon resonance which is applicable to semiconductors. This theory accounts for the nonlinear dispersion in these media which causes deviations from Kerr-type behavior. For ultrashort pulses the nonlinear dispersion becomes significant and causes shock formation, which will limit the nonlinear optical switching capability. However, we have found that when combined with linear dispersion the nonlinear dispersion allows for soliton propagation. We predict that these solitons should propagate in quantum dot doped waveguides, and that they should allow for improved all-optical switching (soliton switching).

In other work, we have been studying the 2D motion of cold atoms in an annular laser beam or donut mode. This configuration has previously been studied but with the aim of trapping the atoms in the center of the donut via the dipole force, hence creating a high density of atoms. In contrast, we have been studying the case where the atoms are trapped along the peak of the laser mode, hence creating a two-dimensional rotator. This provides an atom optics realization of a 2D rotator involving a laser cooled two-level atom tightly bound by the light shift (optical) potential supplied by a near-resonant, annular laser beam. This configuration is closely related to previously demonstrated optical traps for laser cooled atoms formed by the light shift potential in a tightly focused Gaussian beam. Here, however, the light field supplies an annular as opposed to a Gaussian light shift potential. Studies of atomic motion in periodic arrays of light shift potential wells formed by laser standing waves, optical lattices, have recently revealed a close similarity to the motion of electrons in a solid, and now show promise as model

systems in which to study condensed matter phenomena. Similarly, the wavelength sized annular trap proposed here approximates a two-dimensional molecular system, with a spectrum of rotational-vibrational eigenstates. We expect this "artificial 2D molecule" to provide a new, well controlled model system for molecular physics, with the obvious advantage that the confining potential and spectrum of eigenstates is exactly calculable. In its ground vibrational state, the system yields a realization of the 2D rotator. To illustrate the novel physics which can be explored using this system we showed that gravity acts analogously to the Stark effect for a charged rotator with an applied electric field.

Finally, we have also been studying the Bose-Einstein condensation in small atomic samples. In particular, we have shown that the macroscopic wavefunction for BECs composed of a few thousand atoms cannot act as an order parameter for the system as it undergoes a series of collapses and revivals, reminiscent of the Jaynes-Cummings model of quantum optics. This work has far reaching consequences for current experiments. In particular, it calls into question the role of the macroscopic wave function and spontaneous symmetry breaking in determining the properties of quantum gases such as superfluidity. Even for the large condensates now reported with 10^6 atoms, the collapse time is much less than a second, so that the collapses should be observable in current experiments.

Personnel Supported

The following people were supported by or involved in JSOP related research:

Ewan M. Wright

Augusto Rodrigues (Ph.D student)

Keith Kasunic (Ph.D student)

Kirk Cook (Masters student)

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11. Q. Feng, J. V. Moloney, A. C. Newell, E. M. Wright, K. Cook, P. K. Kennedy, D. X. Hammer, B. A. Rockwell, and C. R. Thompson, "Theory and Simulation of Laser-Induced Breakdown and Self-Focusing of Ultrashort Focused Laser Pulses in Water," to be published in *IEEE J. Quant. Electron* (1996).

Interactions/Transitions

a. Conference Presentations

The work conducted under JSOP has led to several presentations at conferences which are listed below:

1. Q. Feng, R. Flesch, J. V. Moloney, and E. M. Wright, "Cascade Breakdown Versus Self-Focusing for Femtosecond Pulses in Transparent Media," OSA Annual Meeting/ILS-XI Program, Portland, OR (Sept. 1995).
2. A. C. Newell, Q. Feng, J. V. Moloney, and E. M. Wright, "Eye Damage: The Role of Self-Focusing in Laser Induced Breakdown by Focused Picosecond Pulses in Water and Other Materials," Nonlinear Optics Workshop, Tucson (Oct. 1995).
3. M. Santagiustina and E. M. Wright, "Linear and Nonlinear Dispersion in Solid-State Solitary-Wave Lasers," contributed paper, OSA-IEEE XI Advanced Solid State Lasers Topical Meeting, San Francisco, CA (1996).
4. A. M. Dunlop, W. J. Firth, and E. M. Wright, "Generalized Mean-Field or Master Equation for Nonlinear Cavities with Transverse Effects," contributed paper, CLEO 96, Anaheim, CA (1996).
5. L. Torner, W. E. Torruellas, G. I. Stegeman, and E. M. Wright, "Trapping of Light Beams and Formation of Spatial Solitary Waves in Quadratic Nonlinear Media," invited paper, CLEO 96, Anaheim, CA (1996).

6. B. L. Lawrence, W. E. Torruellas, G. I. Stegeman, and E. M. Wright, "Stable Self-Trapping and Ring Formation in PTS," contributed paper, CLEO 96, Anaheim, CA (1996).

7. W. Forysiak, J. V. Moloney, and E. M. Wright, "Dynamic Nonlinear Optical Skin Effect," contributed paper, IQEC XX, Sydney, Australia (July 1996).

8. E. M. Wright, D. F. Walls, J. C. Garrison, "Collapses and Revivals of Bose-Einstein Condensates Formed in Small Atomic Samples," contributed paper, IQEC XX, Sydney, Australia (July 1996).

b. Consulting

I have been involved in no consulting or advisory functions.

c. Transitions

As part of my JSOP sponsored work I have been involved in the development of computer codes for modelling nonlinear pulse propagation in water and related media. In particular, these codes have application in studying laser eye-damage mechanisms, and have been transferred to Brooks Air Force Base for that purpose. This work is also part of funding for the Arizona Center for Mathematical Sciences through the Armstrong Laboratory at Brooks.

Discoveries/Inventions/Patent Disclosures

None

Honors/Awards

None

REAL-TIME ELECTRONIC HOLOGRAPHIC MOIRE

Katherine Creath

This report is for work performed between 11/1/94 and 6/1/95.

Objectives

The goal of this work was to develop a real-time electronic holographic moire system for simultaneously measuring in-plane and out-of-plane displacement and stress of mechanical components.

Status of Effort

As reported last year, we were able to get some initial measurements. However, we were limited by noise in the measurements and were unable to unambiguously remove phase discontinuities. Our subsequent work has concentrated on this. During the JSOP review on 2/14/95 I reported preliminary results showing how we have been able to overcome this problem. However, after that review, the next funding increment was not approved. Therefore, we finished up the task we were working on and have not continued this project.

Personnel Supported

Students Norbert Sigrist and Joanna Schmit

Visiting Scientist Peter Ettl

Publications

The work of the last year is summarized in a paper submitted to Applied Optics. I am currently making minor revisions asked for by the reviewers and expect it to be published in about 6 months. The title of the paper is "Comparison of phase unwrapping algorithms using gradient of first failure." The reviewers both liked the idea of having a simple quantitative means for determining the success or failure of a particular algorithm. There still needs to be more work done comparing algorithms, but this first step is in the right direction.

Inventions/Patent Disclosures

None

Honors/Awards

None

DEVELOPMENT OF A GENERALIZED ASPHERIC INTERFEROMETER

John E. Greivenkamp

Objectives

The purpose of this program is to develop an interferometer system that does not require use of additional null optics to test aspheric optical surfaces. Previous work demonstrated measurement of several hundred waves of departure from a reference sphere. Without null optics, aberrations are introduced at the test part and propagate through the interferometer (Figure 1), requiring calibration to relate the measured wavefront to the part shape. This project is an attempt to provide a method of interferometric system calibration in the presence of aspheric wavefronts. The method involves modeling the interferometer using a lens design program.

Status of Effort

The approach used is termed reverse optimization. The interferometer optics are measured as accurately as possible. This includes the element spacing as well as the approximate test part location. This nominal interferometer prescription is entered into the lens design program. The actual OPD measurements from the interferometer (using the measured fringe pattern) are entered as targets or goals in the merit function. The program is then told to optimize the system by adjusting the prescription to match the targets. The result of this operation should give a unique (and correct) solution to the interferometer design. The test part shape, which is the ultimate unknown, will also be computed.

Accomplishments

Aspheric surface testing would be greatly expedited by eliminating the need for a null condition. To test in a non-null configuration, an interferometer must be capable of measuring steep wavefronts. These wavefronts contain aberrations introduced by the interferometer optics, so non-null measurements must be calibrated.

Sub-Nyquist interferometry (SNI) enables measurement of large wavefronts. A simple Twyman-Green interferometer was constructed to conduct SNI and to explore the calibration problem (Figure 2). The characteristics of the interferometer were investigated, and wavefronts with several hundred waves of departure from a reference sphere were recorded and successfully reconstructed. A defocused sphere was used to demonstrate the need for calibration and to serve as a test subject for the calibration study.

Reverse optimization was used to calibrate wavefront measurements. Experimental wavefront data were entered into the merit function of a lens design program, and optimization was employed to retrieve the prescription of the interferometer and the part shape. The variables used in the reverse optimization operation are shown in Figure 2. To simulate interference in the design program, the reference wavefront was stored in a Zernike phase surface on the image plane. The multiple configuration mode of the program was utilized to optimize several test configurations simultaneously, providing additional information to overcome a global optimization problem and to remove uncertainty in the part alignment. Errors introduced by pupil distortion were

avoided by moving the stop to the plane of the sensor in the design program. Measurements from a defocused sphere were successfully calibrated using reverse optimization. A surface departure of 100l was calibrated to better than l/4 PV.

The results of this calibration are shown in Figures 3 and 4. With no system calibration, the measurement error is 0.66 waves peak to valley (Figure 3). After the reverse optimization procedure, this error drops to 0.12 waves peak-to-valley (Figure 4).

Because the interferometer could not be characterized sufficiently for calibration of measurements from aspheres, simulations were conducted. A lens design program was used to develop an accurate model of an interferometer, including simulated fabrication, alignment, and characterization errors. Reverse optimization was applied using wavefronts generated by the model. Testing was simulated for several conic asphere surfaces. Reverse optimization yielded calibration to l/4 PV for conic aspheres with surface departures as large as 300l (Figure 5). The results suggest that it is feasible to calibrate non-null measurements of aspheric surfaces using reverse optimization.

Personnel Supported

Andrew Lowman completed his Ph.D. as a result of this effort. The title of his dissertation is "Calibration of a Non-Null Interferometer for Aspheric Testing."

Publications

1. A.E. Lowman and J.E. Greivenkamp, "Interferometer Errors Due to the Presence of Fringes," submitted to OSA Engineering & Laboratory Notes (1995)

2. A.E. Lowman and J.E. Greivenkamp, "Modeling an Interferometer for Non-Null Testing of Aspheres," presented at Optical Manufacturing and Testing, Proc. SPIE (San Diego, July 1995).

In addition, three journal articles describing this work are in preparation for submission to *Optical Engineering* and *Applied Optics.*

Interactions/Transitions

We have had significant interaction with the Center for Optics Manufacturing (COM) on this project. COM is an Army-funded program headquartered at the University of Rochester. COM's primary funding has come from the Army Mantech Program. This technology is important to COM as they develop automatic process for the fabrication of aspheric optics.

This work also serves as the basis for our proposed work under the current ARPA Broad Agency Announcement on Physical Optics. That program requires the measurement of a large variety of non-rotationally symmetric wavefront and surfaces, and the technology developed under this program appears to be critical to the implementation of aerodynamically conformal windows to aircraft and missiles.

Inventions/Patent Disclosures

None

Honors/Awards

None

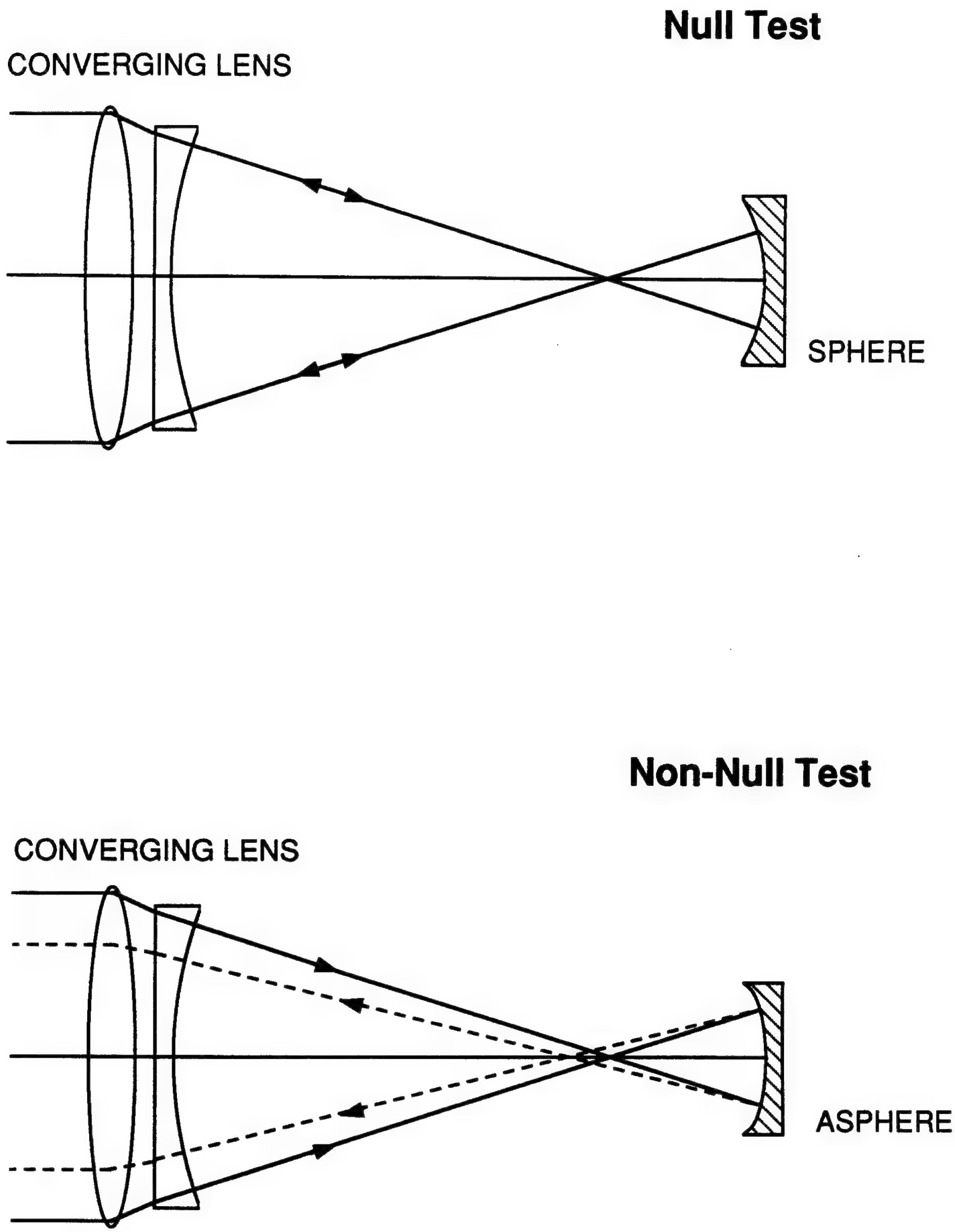

Figure 1 - Aberrations are introduced into the test in non-null configurations due to the change in the path through the optical system. In a null configuration the rays retrace themselves.

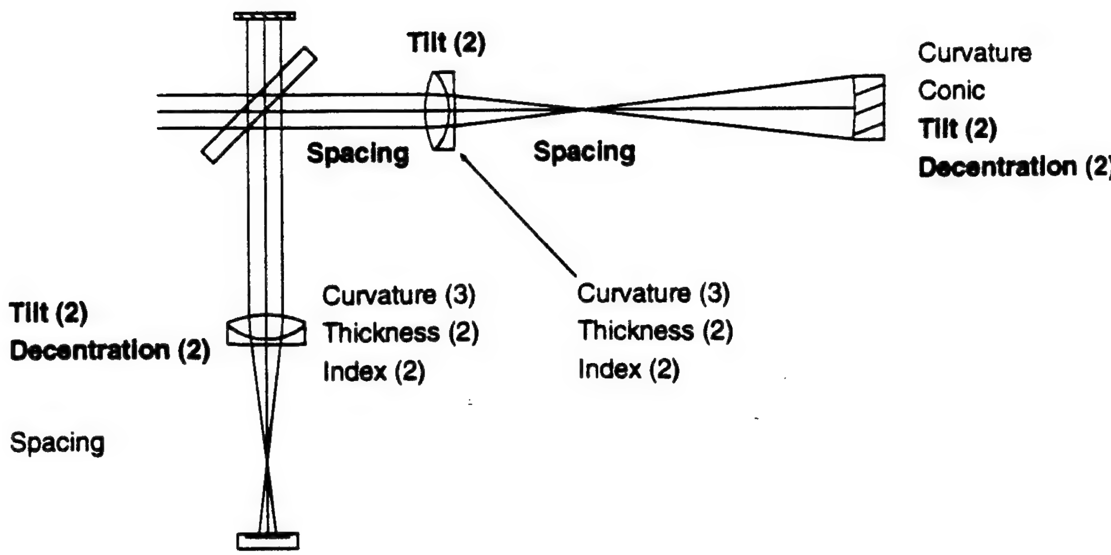

Figure 2 - Twyman Green interferometer, with potential variable for reverse optimization shown. The actual variables use are in bold.

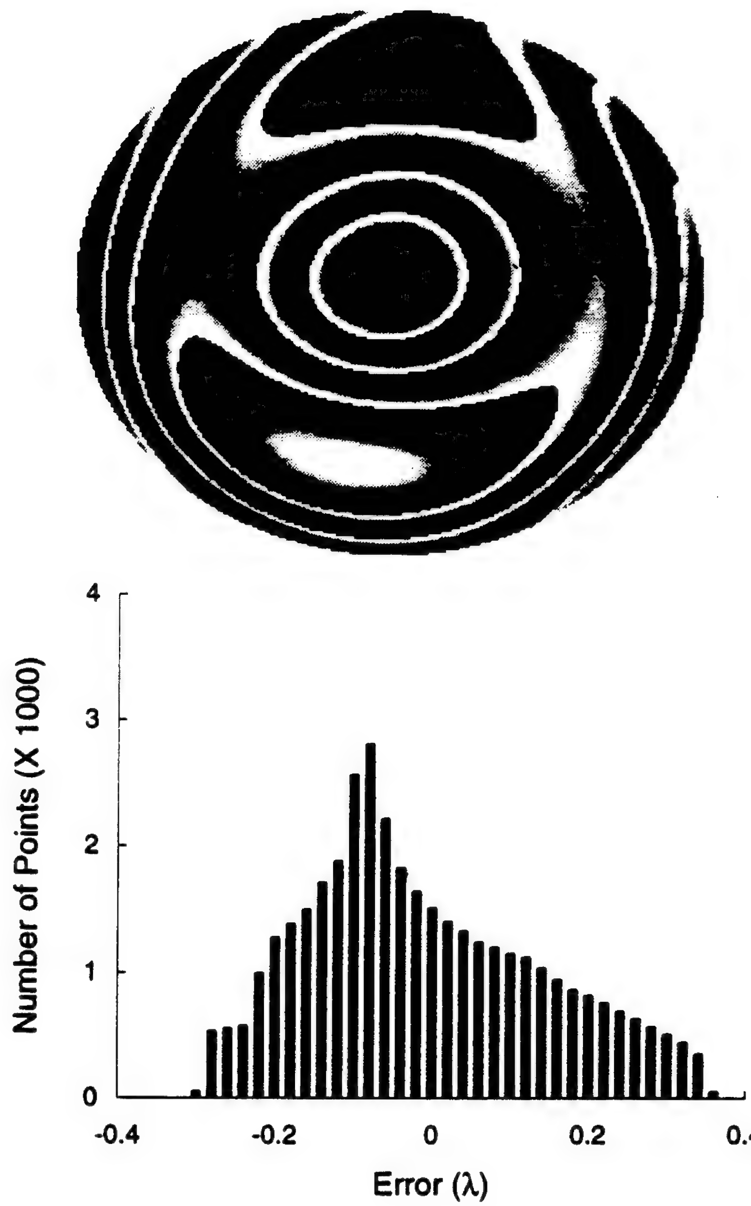

Figure 3 - The uncalibrated error in testing a defocused sphere with 100 waves of departure: 0.66 λ PV.

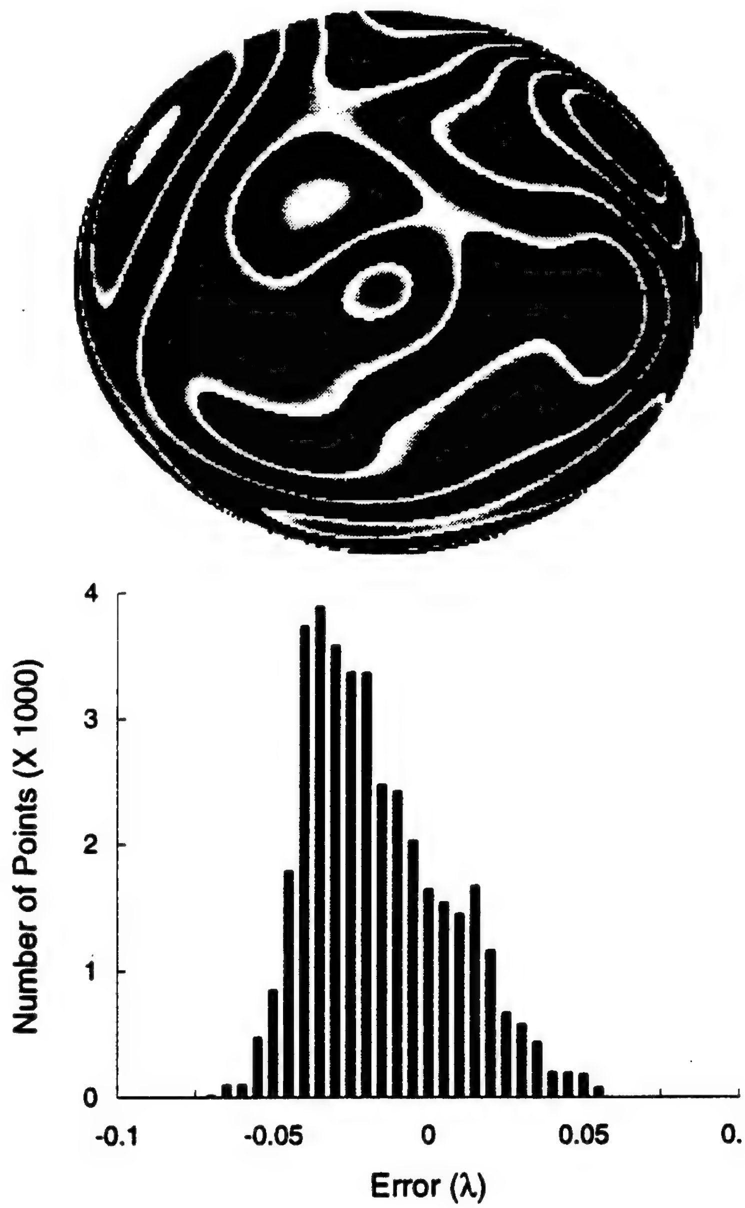

Figure 4 - The error after calibration with reverse optimization in testing a defocused sphere with 100 waves of departure: 0.12 λ PV.

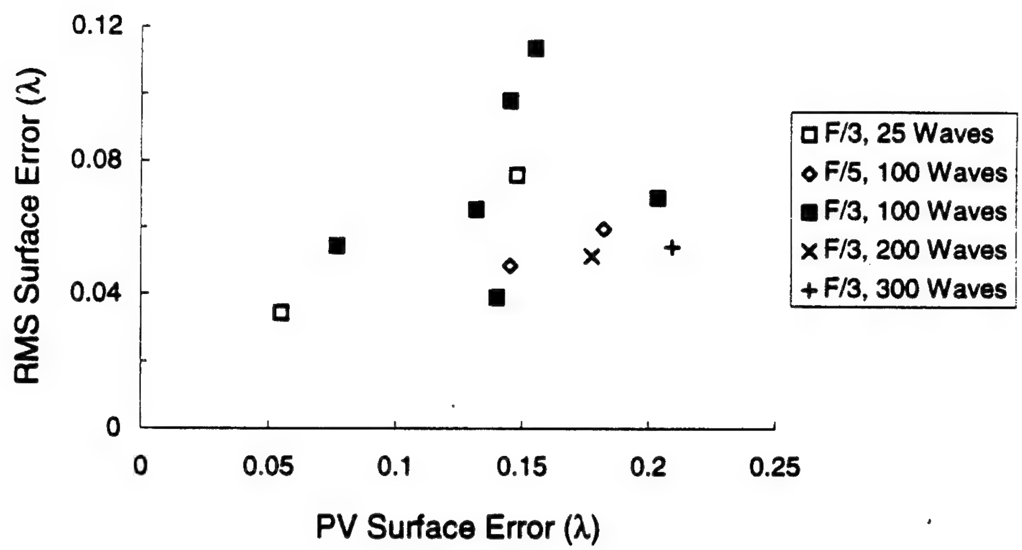

Figure 5 - Results of simulation showing the reverse optimization calibration of aspheric surfaces with departures ranging fro 25 to 300 waves.

WIDE FIELD-OF-VIEW MICRO OPTICS

T. D. Milster

Research Findings

Objective

This report summarizes the work accomplished for JSOP over the last several years. We started by studying wide field-of-view micro-optics. This is an interesting topic, but we found that it is very difficult to write submicron holographic patterns on curved substrates. The research effort then divided into two areas. First, we investigated writing micro lithographic patterns with a near-field optical microscope (Froehlich *et al.*, 1992). Second, we started to investigate other ways to make lithographic patterns on curved substrates, such as using direct writing with a focused laser beam. This part of the project eventually grew into a collaboration with Steward Observatory for making holographic null correctors for large-format telescope secondary mirrors (Vernold and Milster, 1994). Several interesting questions were answered, such as how to write a large hologram without photoresist and how to align optical and mechanical axes to submicron levels (Milster and Vernold, 1995). The major thrust of the project, however, became our research in near-field scanning optical microscopy (NSOM). The remainder of our report discusses progress on NSOM.

Status of Effort

Near-field microscopy uses a subwavelength aperture scanned in proximity to the sample surface. Light shines through the aperture and illuminates the surface in a local

region. The transmitted light is collected some distance away from the sample with sensitive detectors. As the aperture scans the sample, local variations in optical properties produce modulation in the transmitted light, and a signal is recovered from the detectors. An image of the optical properties of the surface is produced by correlating the detector output with the scan position.

Our NSOM work is divided into two areas, which are modeling and experiment. The modeling effort uses a hybridization of finite-difference-time-domain (FDTD) calculations and angular spectrum calculations. The FDTD code is used to find the interaction of the light and the sample. The angular spectrum code calculates the light distribution at the detectors. The angular spectrum calculations are straightforward on a personal computer, but the FDTD calculations require a significant computing resource. The experimental work involves building working NSOM devices and studying their performance. We are currently on our third generation device.

Significant accomplishments of our modeling studies are listed below:

Accomplishments

1) Kann *et al.*, 1995a, show that the output of an NSOM tip is collimated for a distance approximately equal to the aperture radius. The light then diverges linearly. The phase of the near-field distribution is examined for the first time.

2) Kann *et al.*, 1995b, show a detailed investigation of the relationship between the sample's index of refraction, probe-to-sample separation, and transmitted power. Two detection techniques, which are differential and total detection, are presented that

each offer certain advantages. The differential technique has not been described previously and is more robust to variations in probe-to-sample separation.

3) Kann *et al.*, 1995c, show that a linear systems analysis of NSOM devices is reasonable over a limited range of sample parameters. Characteristics of the transfer function are described.

4) Kann *et al*, 1995d, describe various heating mechanisms between the probe and sample. By coupling a finite-difference thermal model with the FDTD code, we show that the four heating mechanisms in the sample are: 1) direct optical transfer and absorption; 2) reradiated optical transfer and absorption; 3) thermal conduction; and 4) thermal radiation. For most NSOM probes, thermal conduction and thermal radiation exhibit minor influences on sample heating. Optical power emitted by the probe and absorbed in the sample plays the greatest role in heating the sample, but reradiated optical power can have a significant effect if the polarization out of the probe is oriented in the plane of observation.

The significant accomplishments of the NSOM experiments are listed below:

1) Froehlich and Milster, 1994, show that the minimum detectable displacement of an NSOM tapered fiber probe using a shear-force servo is 2.8×10^{-3} Å $_{rms}/\sqrt{Hz}$. This is within one order of magnitude of other techniques used in high resolution atomic force microscopy (AFM). Therefore, the servo used in our NSOM microscope enables the acquisition of both images of optical surface properties with ultra-high resolution and images of the surface topology that are comparable with AFM.

2) Froehlich and Milster, 1995, discuss the operation of the shear-force servo used in our NSOM instrument. Theory and experiment are in reasonable agreement. The tradeoff between sensitivity and stability is described in detail.

3) In yet unpublished work, Froehlich and Milster describe the nature of the tip vibration amplitude reduction that is fundamental to the operation of shear-force servos. We first locked the servo using the second resonance of the probe tip. Then we added a swept dither signal to the probe tip near the first resonance frequency. The dither vibration amplitude versus frequency at the first resonance was measured. Results are shown in Fig 1(a) - (e). Probe-to-sample separations are: a) far from the surface; b) 4.7 nm; c) 3.1 nm; d) 1.9 nm; and e) 0.66 nm. The increasing width of the response curves with closer spacing indicates that the reduction in probe dither amplitude is due to increased damping and not a change in the resonance frequency.

4) Also in yet unpublished work, Froehlich and Milster have shown a dramatic example of the usefulness of NSOM when studying phase-change marks in optical recording media. Figure 2(a) shows the topology of a sample surface where 600 nm diameter crystalline marks are written into an amorphous thin-film layer on top of a glass substrate. The surface features around the marks are due to crystallographic grain boundaries. The maximum deviation of the surface in the mark regions is 8 nm, so the sample is essentially flat. Figure 2(b) shows the NSOM image. Notice that no correlation is observed with the topographical information found in Fig. 2(a). The striking optical contrast (~50%) in the mark areas clearly shows the subsurface optical

characteristics of the thin film. In addition, the bright spot in the center of the marks is not an intuitive result. Far-field microscopes, which have much lower resolution, do not show this feature. However, our modeling has shown that the bright spot is a real effect, and its properties depend on the shape of the walls of the marks below the surface of the sample.

Personnel Supported:

Finally, this project has been responsible for the graduation of two Ph.D.s in Optical Sciences. Dr. Kann now works at USAF Rome Laboratory and was sponsored in part by the Senior Knight Program. Mr. Froehlich (soon to be Dr. Froehlich) will be seeking employment after returning from a bike tour in New Zealand.

Publications

1. J. L. Kann, T. D. Milster, F. F. Froehlich, R. W. Ziolkowski, and J. Judkins, "Numerical analysis of a two-dimensional near-field probe," Ultramicroscopy **57,** 251-256 (1995a).
2. J. L. Kann, T. D. Milster, F. F. Froehlich, R. W. Ziolkowski, and J. Judkins, "Near-field optical detection of asperities in dielectric surfaces," J. Opt. Soc. Am. A, **12,** 501-512 (1995b).
3. J. L. Kann, T. D. Milster, F. F. Froehlich, R. W. Ziolkowski, and J. Judkins, "Linear behavior of a near-field optical scanning system," J. Opt. Soc. Am. A **12,** 1677-1682 (1995c).

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6. T. D. Milster and C. L. Vernold, "Technique for aligning optical and mechanical axes based on a rotating linear grating," Opt. Eng. **34**, 2840-2845 (1995).

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8. C. L. Vernold and T. D. Milster, "Non-photolithographic fabrication of large computer-generated diffractive optical elements," Soc. Photographic and Inst. ng. Proceedings Volume **2263**, pp. 125-133 (1994).

9. F. Froehilich, T. D. Milster and R. Uber, "High resoltuion lithography with a near-field scanning sub-wavelength aperture," Soc. Photographic and Inst. Eng. Proceedings Volume **1751**, pp.312-320 (1992).

Degrees

J. L. Kann, "Numerical Modeling of a near-field optical system," Ph. D. University of Arizona, 1995.

F. F. Froehlich, "Resolution and contrast of optical and shear force imagery in near-field scanning optical microscopy," Ph. D. University of Arizona, (final defense scheduled December 18, 1995).

Inventions/Patent Disclosures

None

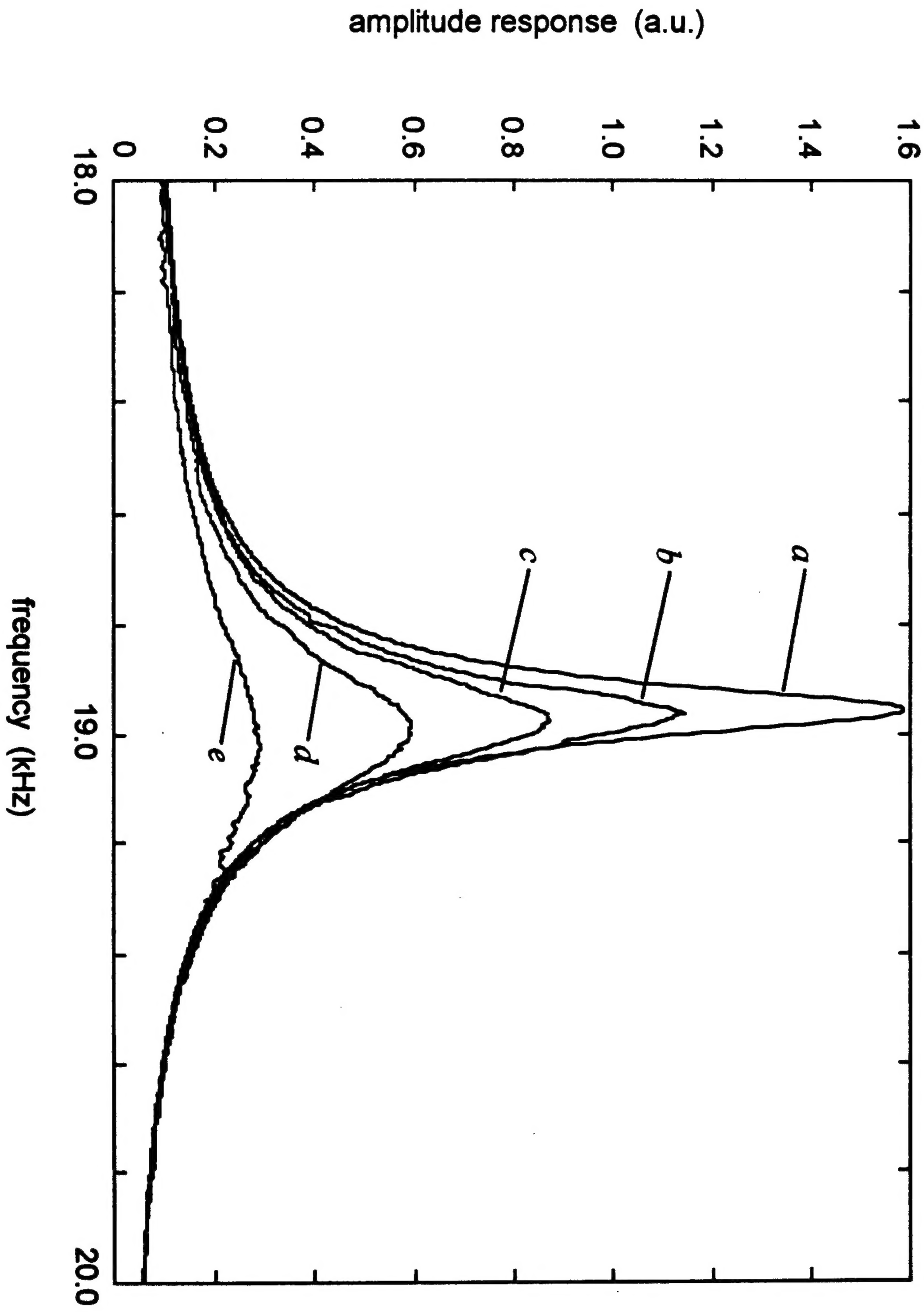
Honors/Awards

None

Figure Captions:

1. NSOM probe frequency response at the first resonance for several probe-to-sample separations: a) far from the surface; b) 4.7 nm; c) 3.1 nm; d) 1.9 nm; and e) 0.66 nm. The increasing width of the response curves with closer spacing indicates that the reduction in probe dither amplitude is due to increased damping and not a change in the resonance frequency.

2. Crystalline marks in an amorphous thin-film background produce: (a) topographic scan showing ~ 8 nm high grain boundaries in the regions of the 600 nm diameter crystalline marks. (b) NSOM image showing the optical properties of the marks resolved to 50 nm. Notice that the topographic and optical images are not correlated, which indicates that NSOM is producing new information about the surface optical properties.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0.4
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frequency (kHz)
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Figure 1

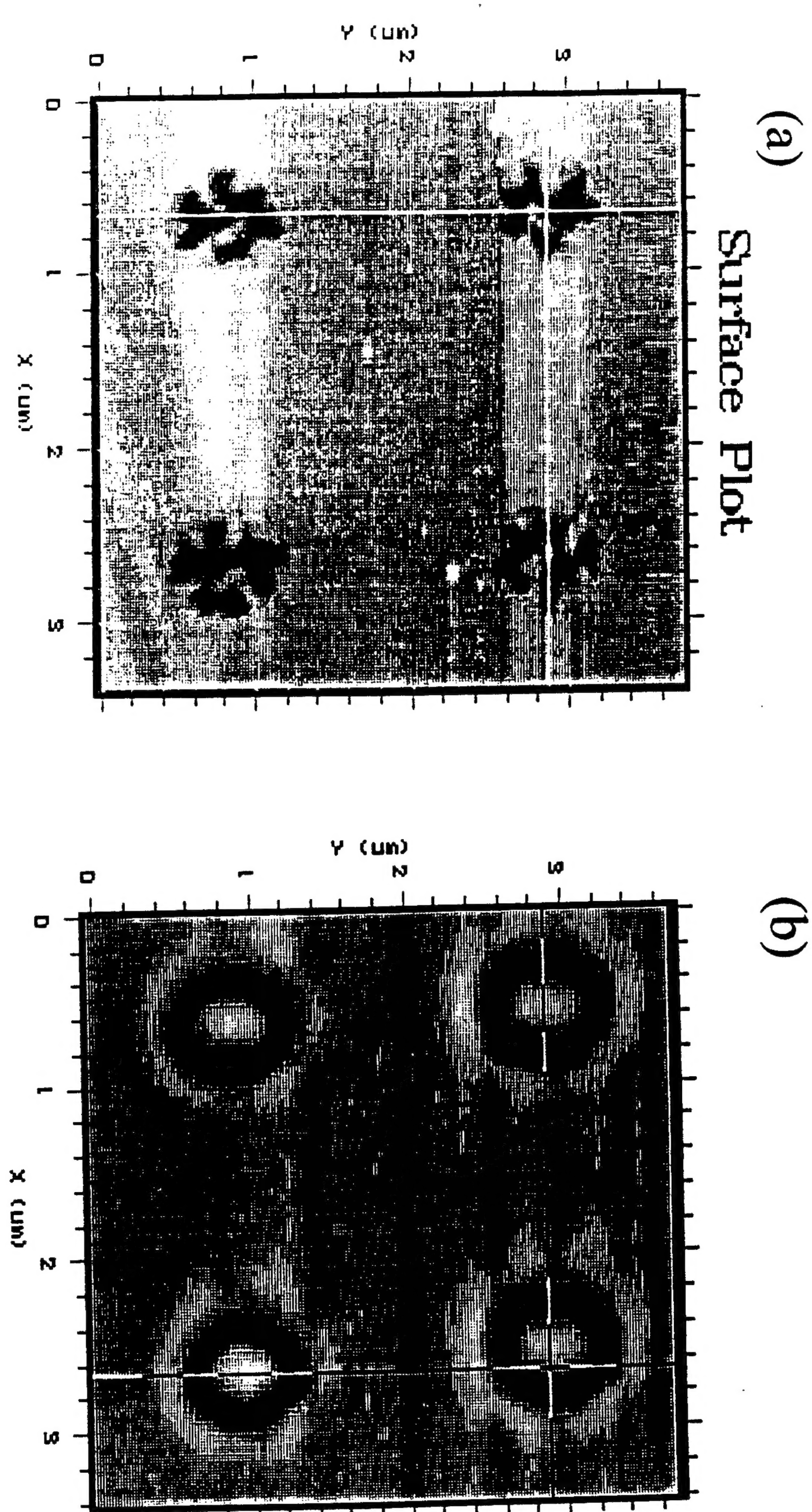

Figure 2